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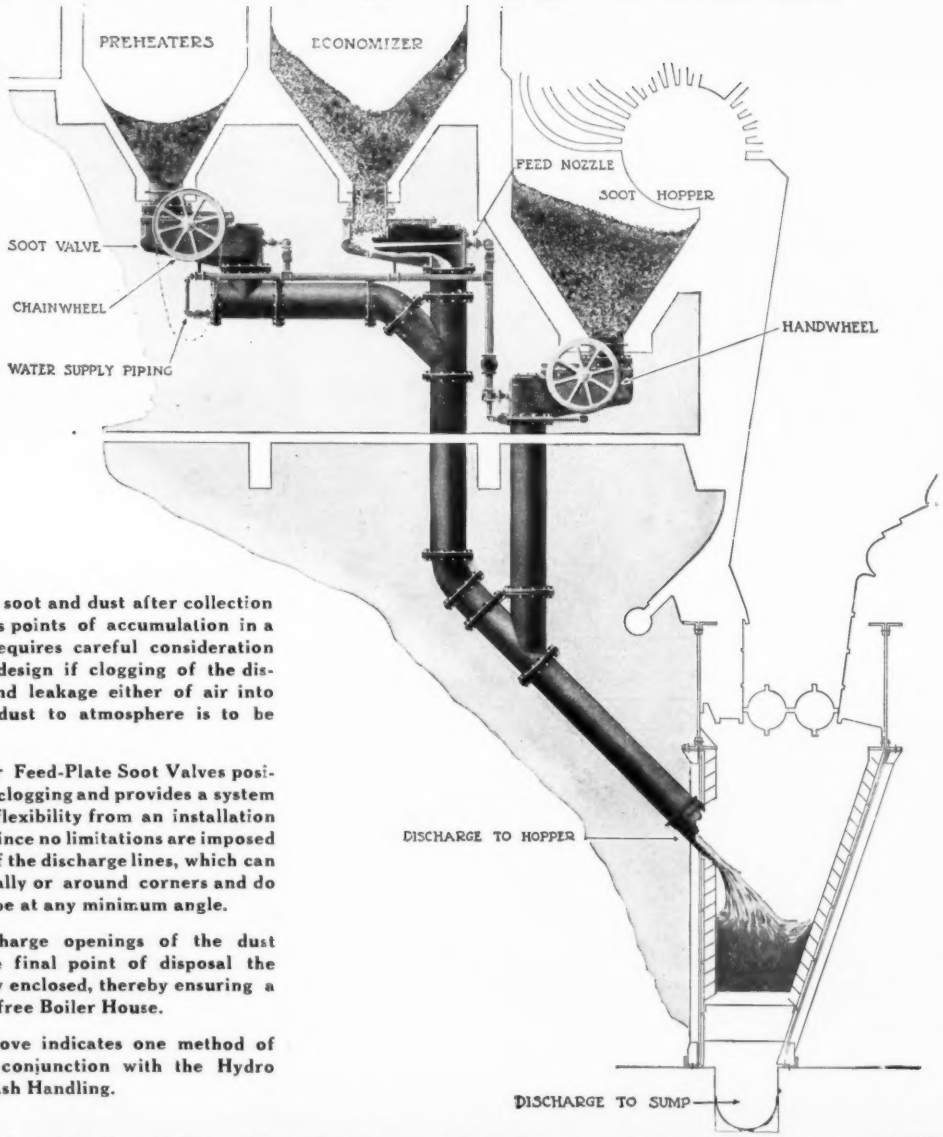

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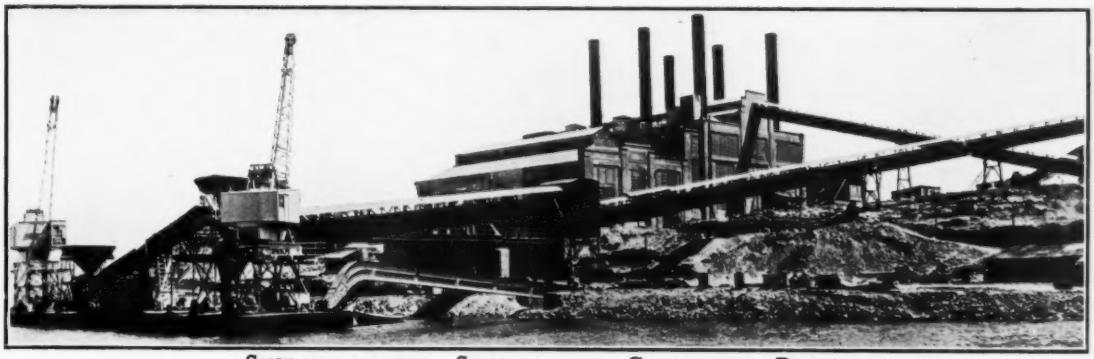

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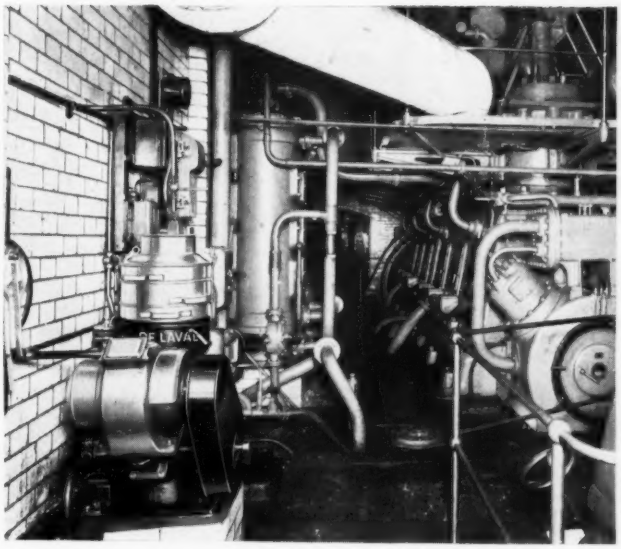

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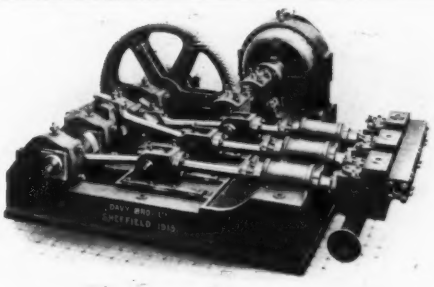

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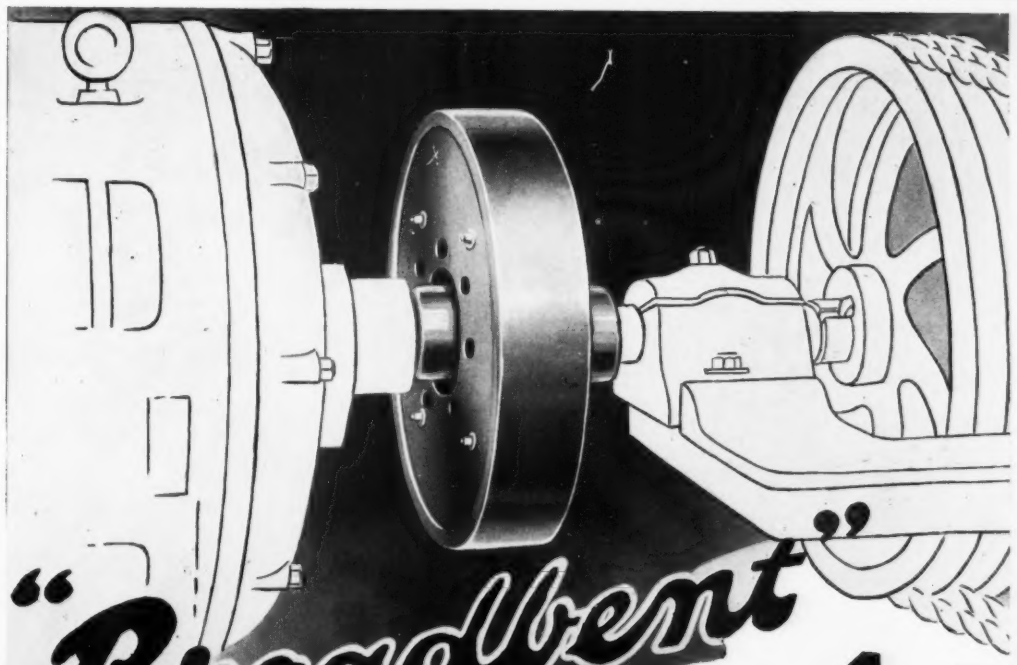

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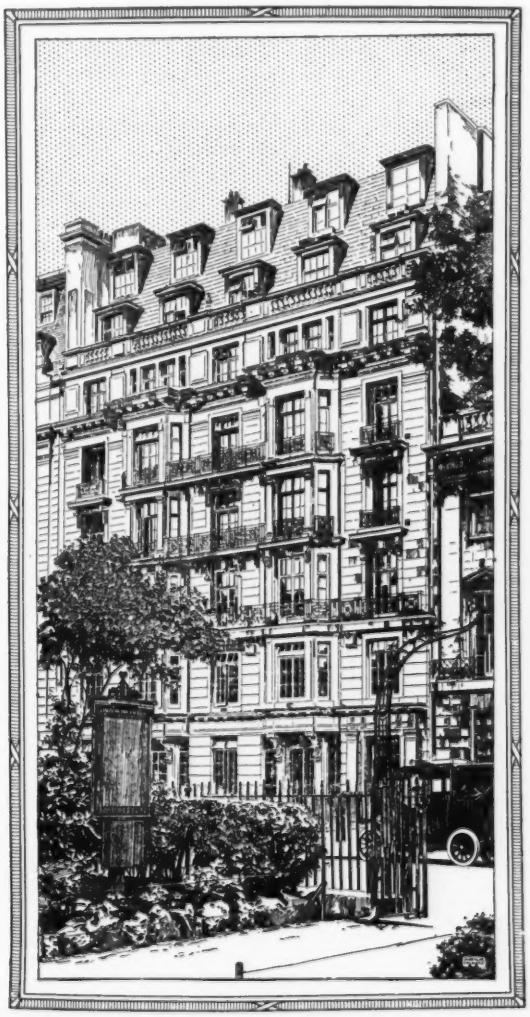

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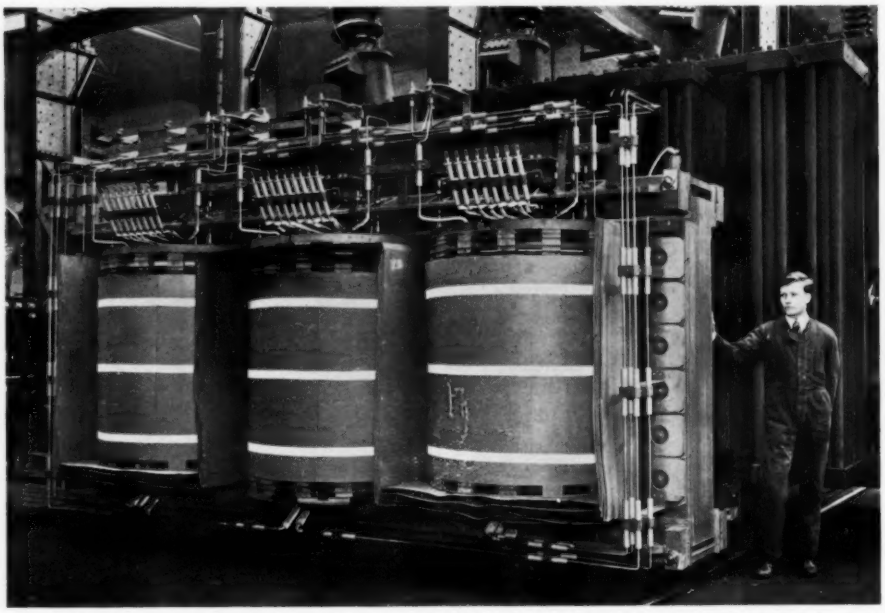
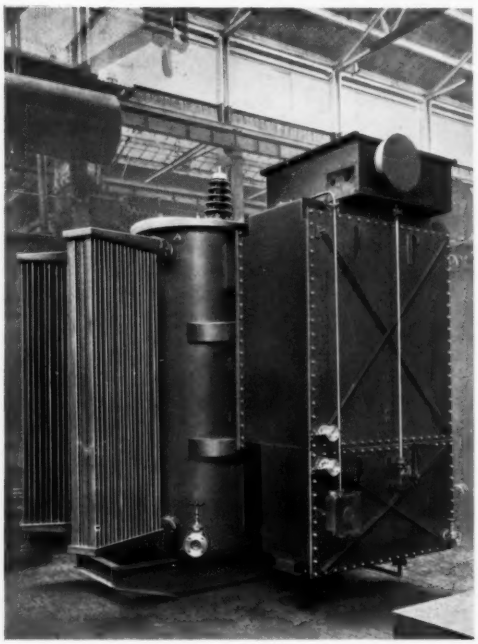
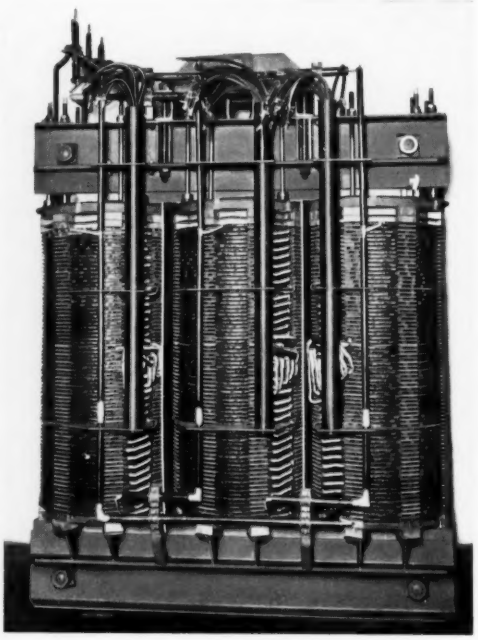


Core & Windings of a Transformer for the "Grid." This is a 132 *kV.,* 15,000 *kVA.,* 3*-phase unit with* 5*-limb core. It is now operating on the Central Scotland Scheme.*





Transformers for Secondary Transmission Lines of the Central Electricity Board. These are 33*kV. units; that on the left is a complete* 5,000 *kVA transformer with On-load Tap-changing Gear, while the Core and Windings are of an exactly similar unit of* 7,500 *kVA.*

The English Electric Journal

Vol. V. No. 1 JANUARY, 1930 One Shilling.

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All Communications respecting Editorial Contents should be addressed to The Editor, The English Electric Journal, Queen's House, Kingsway, London, W.C.2.

PROGRESS.

Whatever the deficiencies of the past year may have been, certain redeeming features stand out prominently against the somewhat dark background with which it is generally depicted. The Electricity Act and the ensuing National Electricity Schemes have not lacked criticism, but none connected with the technical side of the electrical industry will deny that these schemes have given an impetus to the perfecting and general expansion of electrical manufacture in this country. Large electrical plant in particular has been developed to an extent which enables the British manufacturer to compete with full confidence for the equipment of the largest and most modern schemes of electrical development in any part of the world.

The English Electric Company may justifiably claim to have made marked progress in all branches of its activities, and the succeeding pages give a general indication of what has been accomplished in the field of transformer production alone. Transforming and allied apparatus of every type and size, and for every voltage and class

of service are now being handled, not only in considerable volume, but also with the aid of the most up-to-date equipment and manufacturing processes.

Many of the largest units are for Electricity Schemes in this country and abroad, for which also important High-voltage Switching Equipments are being manufactured on as large and diverse a scale. In a subsequent issue we hope to publish particulars of some important installations for 132 kV. and lower voltages that are now being prepared for service.

Within the limits of this editorial, mention may be made only of the Company's heavier products, but this would not be complete without some indication of what has been achieved in the Power Station field. Of the many large steam and water-power plants supplied, two may be singled out as representative and of special interest.

The largest 3,000 r.p.m. steam turbo-alternator set in this country has recently been under steam in the power house of the West Ham Corporation; this is one of the Company's 30,000 kW. multi-cylinder sets, for the installation of which Mr. F. W. Purse, M.I.E.E., was responsible before his appointment as Chief Electrical Engineer to the London and Home Counties Joint Electricity Authority.

The completion of the tunnelling work in connection with the Lochaber Hydro-electric Scheme of the British Aluminium Company and its associates has recently directed public attention to that important enterprise. The main power station plant, comprising some 50,000 h.p. of water turbines and electric generators of special design, has been manufactured by this Company, and has undergone its introduction to service with most satisfactory results. The switching installation has also been supplied by this Company.

A High-Voltage Testing Laboratory.

The complete "English Electric" equipment described below is in many ways one of the most advanced installations of its type yet constructed. It has been erected in the Cable Testing Department of Messrs. Siemens Brothers & Co., Ltd., at Woolwich.

The great development in the size and scope of electricity supply schemes and the general use of much higher voltages has led to completely new problems for the cable manufacturer and a rapid development in the technique of cable construction, with a corresponding demand for more thorough testing and research.

The plant to be described has been designed for the testing of single-core cables for working at pressures up to 76 kV. to ground, i.e., on 132 kV. 3-phase systems, and of three-core cables which will operate at 66 kV. between cores.

Unlike most H.V. testing equipments, those used for cable work are far more concerned with measurements than merely with breakdown tests. The present plant is, therefore, designed for making measurements up to 100 kV. and other testing, breakdown, flashover, etc., up to 450 kV.

On account of the necessity for accurate measurement of small losses at very low power factor, the voltage wave form must be kept free from harmonics, and this makes it desirable that the whole plant including the source of supply should be designed as one unit.

The Testing Department has three enclosed areas surrounded by expanded metal screens 7 ft. high, with one gate only to each area. The large central area contains all the H.V. apparatus. The end compartment adjacent to the H.V. transformers forms the sample-testing area in which breakdown and flashover tests are conducted, and contains a pit for steam-heated oil tanks. The other end compartment is for routine and cable heating tests carried out on drums of finished cable which may be either on the floor, supported on insulated trestles or immersed in steam-heated tanks. There is also

provision for testing lengths of cable buried in an outdoor concrete trench, which may be filled in with soil of various kinds.

One side of these enclosures is bounded by the wall of the building. Along the other side is a gangway from which the testing staff may read the various instruments within the enclosure, either by means of telescopes fixed to the screen, or on transparent scales from reflecting instruments.

Between the gangway and the outer wall are the Machine Room, Regulator Room, Dark Room, and Stores, above which are the Control Gallery and Office, from which the whole of the testing areas can be viewed.

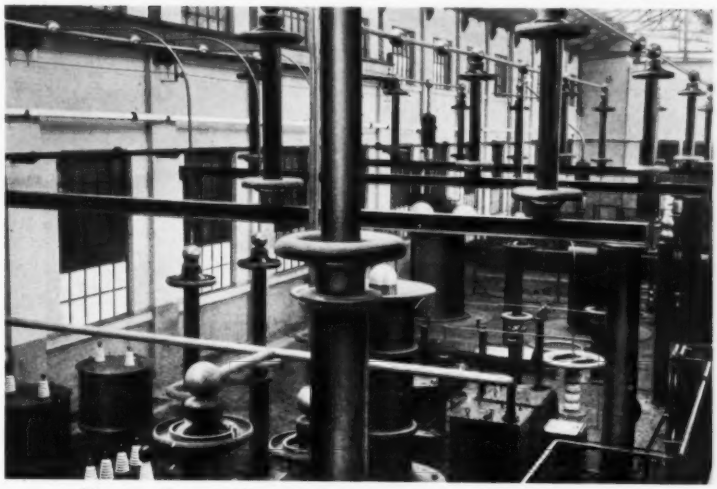


Fig. 1.—General View of Equipment from Control Gallery.

Fig. 1 shows a general view of the testing area from the Control Gallery.

Power is furnished by a 525-kVA., 550-volt, single-phase alternator, driven by a three-speed A.C. motor, which permits the frequency to be 50, 37·5 or 25 cycles per second. By making tests at these frequencies it is possible to deduce the performance of the cable at any commercial frequency. A separate motor-driven exciter is provided.

Fig. 2.—Potential Divider for Voltmeters.

The alternator was specially designed to give a good wave form, and special precautions were taken to suppress the principal harmonics which are introduced by the varying permeability of the cores of the testing transformers during each cycle. The capacity load of cable testing introduced another problem, and the field strength was proportioned to maintain stability under these conditions without danger of self-excitation.

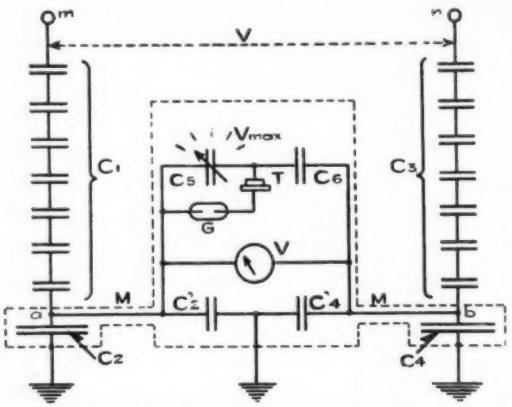
As the stability of the equipment is greater when the alternator field is maintained at its normal value, the voltage applied to the primaries of the testing transformers is varied from 0 to 1,100 volts by means of an auto-connected induction regulator through which the supply is taken. Experience has shown that the wave form is not distorted by the "English Electric" design of induction regulator. The regulator is motor-operated with remote control, and interlock contacts prevent the transformers being connected in circuit unless the regulator is in the position for minimum voltage. Fig. 5, reproduced from an oscillograph film taken on a capacity load, shows that the problem of retaining a practically pure sine wave has been met successfully.

The transformers are of a design specially developed by the English Electric Company for

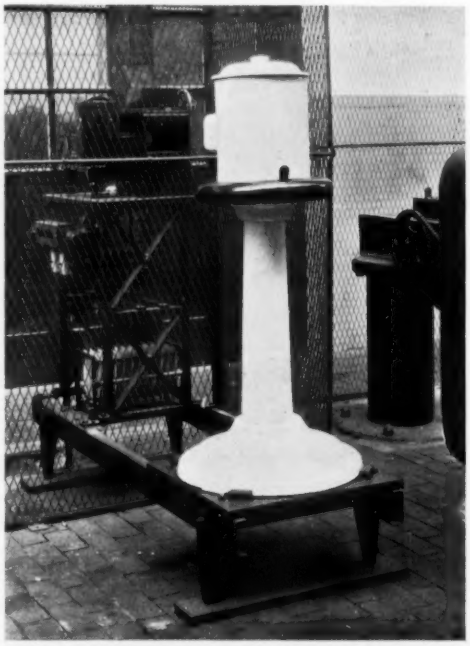
H.V. testing. The H.V. winding is of paper-insulated wire specially treated during manufacture, and the main insulation is fullerboard; the bushings are of the condenser type.

For making pressure measurements alternative equipments are available. A horizontal sphere gap, having 500 m.m. duralumin spheres, is motor-operated from the control desk where a counter shows the separation of the spheres in millimetres; a check scale is provided on the base of the sphere gap.

Although the sphere gap is a standard method of measuring high voltages, it is subject to certain vagaries when used under conditions which are not ideal. Direct-reading instruments are, therefore, used for both effective and crest values of voltage. The type chosen has a potential divider consisting of a series of metal coated porcelain condensers. A large diameter guard plate, on the top, serves to equalise the potential across the individual sections. The potential divider is illustrated in Fig. 2, and Fig. 3 is the connection diagram. In the base is a mica condenser having an electrostatic capacity that is large compared with that of the porcelain condensers, and across this mica condenser is connected an electrostatic voltmeter. Crest voltage is measured by the striking voltage of a Neon tube shunting a variable condenser across the same terminals as the electrostatic voltmeter. This system of voltage measurement is independent of atmospheric conditions and dust accumulation, which have a marked effect on sphere gap measurements.



G = Neon Tube. T = Telephone.
M = Earthed Screen.
Fig. 3.—Voltmeter Connections.



Figs. 4 and 5.—Oscillograph and Portion of Film taken under Working Conditions.

An oscillograph is provided for observation and recording of wave form up to the limit of the measuring instruments, i.e. 100 kV. The vibrators are contained in the porcelain structure shown in Fig. 4, and the cinematograph film camera, automatic-feed arc lamp, and observation mirrors are on the safe side of the fence. Fig. 5 is reproduced from a portion of film taken under working conditions.

High-voltage tests can be applied in this

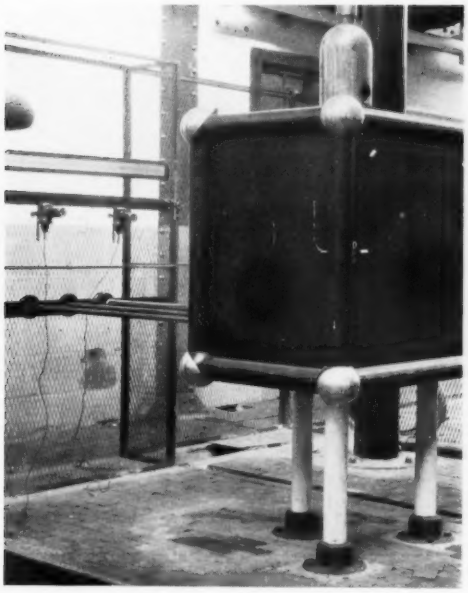


Fig. 6.—"Resistance Measuring Cupboard."

equipment, to cables which are carrying a current corresponding to their working or other load. For this purpose there is a loading transformer of 50 kVA. having an output of 300 amps. at 167 volts, and with its secondary winding insulated for 100 kV. from earth. The cable current is led through a "Resistance Measuring Cupboard" (Fig. 6) which contains a 2-volt heavy traction type accumulator together with a standard ·01 ohm shunt, hot-wire ammeter and voltmeter, a reflecting galvanometer insensitive to commercial frequencies, a reflecting astatic wattmeter, and switching arrangements. It is possible with this arrangement to compare the galvanometer deflection across the cable and shunt, and so plot the temperature rise of the cable against time. Also the true watts may be read and the eddy and sheath losses deduced. Much valuable information can, therefore, be gained under working conditions. Fig. 7 shows the connections; the two instruments in the centre are the wattmeter and the galvanometer.

An important item in testing cables for very high voltages is the measurement of dielectric losses. This is really of far greater importance than breakdown tests on samples, and can be carried out on the complete cable ready for service. Appreciable increase in dielectric loss with increased temperature, the loss not returning to its original value when the temperature is reduced, or increased dielectric power factor with increased applied voltage, would all point to ionisation or other troubles which would render the cable unsatisfactory in use. Losses in the dielectric cause the leading power factor to be slightly above zero corresponding to the small watt component of the current. The power factor and the losses to be measured are so low that every care must be taken that they are not modified in any part of the circuit or in the measuring apparatus if accurate values are to be obtained.

Two methods have been included for measuring the dielectric loss—

(i) Duddell-Mather Wattmeter.

(ii) Schering Bridge.

Until recently the wattmeter was the only method of loss measurement, but the difficulties of measuring losses at a power factor of ·004 are enormous, as the phase angle is less than $0^0 14'$ from true quadrature. It is obvious that potential transformers are useless as the phase angle is

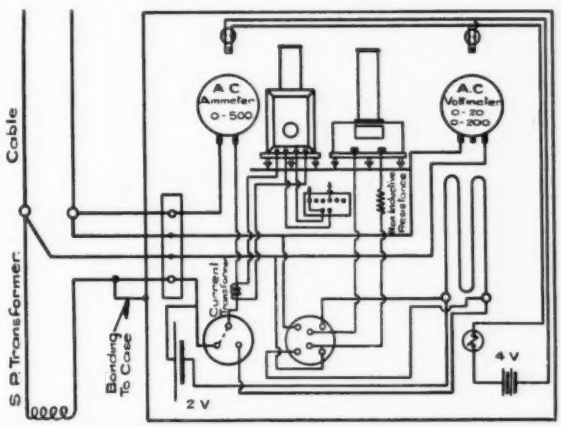


Fig. 7.—Diagram of "Resistance Measuring Cupboard" for Cable Loading.

normally about double this amount and the loss reading may be as much as three times too high, or actually reversed, according to whether the wattmeter current coil is in the H.V. or earth end of the transformer. For this reason Mather woven-gauze resistances have usually been used for H.V. wattmeter potential dividers. Self-capacity in the resistance, and capacity to earth, have led to other phase angle troubles, so that even this was not a complete solution of the problem without very special precautions. It was found that much of this phase displacement was caused through capacity coupling, due to the resistance gauze being mounted on angle-iron framework in steel tanks. The English Electric Company evolved a design in which teak wood supports and a circular bakelised paper tank are used, and the only metal is the resistance wire and terminals. Fig. 8 shows some of the four resistance tanks each containing a 250,000-ohm oil-immersed resistance.

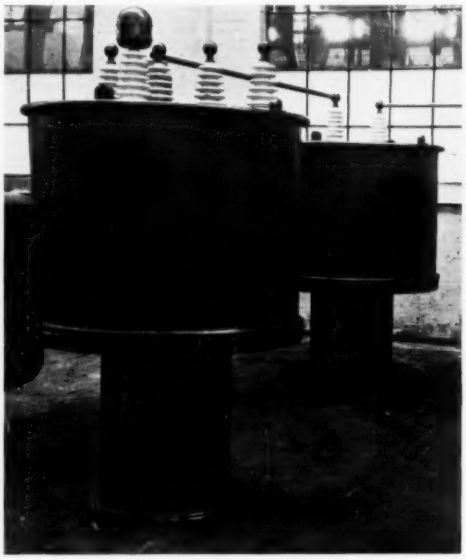


Fig. 8.—Two of the .25 Megohm Resistances.

The wattmeter is, however, only used for routine tests and comparative purposes. Accurate loss measurements are made on the Schering Bridge. A diagram of such a Bridge is shown on page 30 of this number. The bridge consists of a "mixed" load (capacity and resistance), with an adjustable "pure" resistance, balanced against a "pure" condenser and adjustable "mixed" capacity and resistance. The needle type vibration galvanometer is very heavily screened magnetically.

The "pure" loss-free condenser consists of concentric cylinders with air as the dielectric; it is designed for use up to 120 kV. The castings were made, machined and ground to a high degree of precision at the company's Rugby Works. Six months were allowed between the first rough machining and the final grinding, so that all distortion due to casting stresses should have time to settle out between the various machinings, and a permanent laboratory standard condenser result. For the same reason, glass distance pieces were used between the centre electrode and its guard rings. The condenser has a capacity of ·0001 micro-farad, and weighs approximately $1\frac{3}{4}$ tons; Fig. 9 shows a vertical cross section.

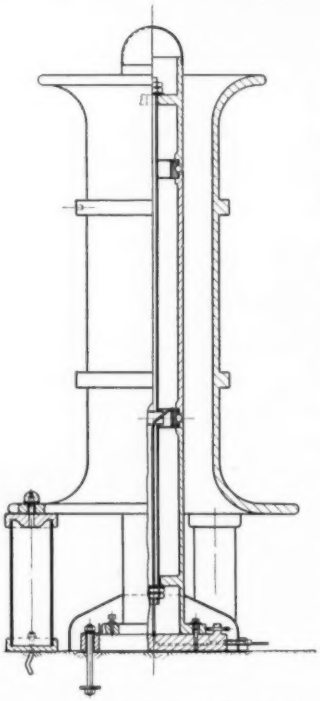
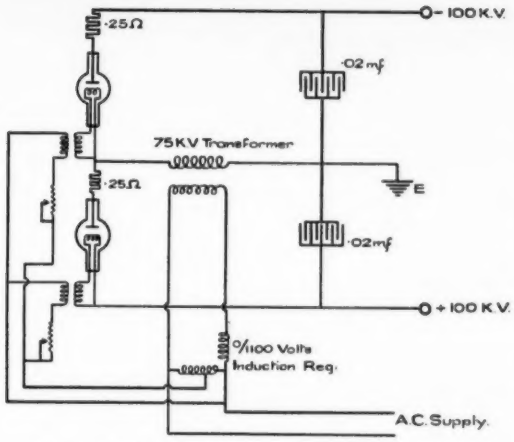


Fig. 9.—"English Electric" Standard Air Condenser for 120 kV.

The values in the arms of the bridge are so calculated that power factor and capacity of the dielectric to be measured are read direct. Accuracy to within ·00001 radian phase angle is obtained, which is 0·25 per cent. on a dielectric of ·004 power factor. For small angles up to about 4°, the sine, tangent and radian measure are the same to four significant figures; the



Figs. 10 and 11.—200 kV. Direct-current Testing Equipment.

power factor and loss of a dielectric are, therefore, expressed as an angle of displacement—decimal fraction of a radian—and this quantity is known as the " phase angle " of the dielectric.

Much information can be gained from the electrification curves of cables by high-voltage direct current, and an equipment for obtaining 200,000 volts D.C. is included in the testing plant. The plant consists of a 5 kVA. Induction Regulator 550/0-1,100 volts feeding a 75 kV. transformer. Full wave rectification is obtained by means of two thermionic valves, and the valves are protected against damage by ·25 megohm " Silit " resistances in the anode circuit. A picture of this equipment is seen in Fig. 10, and the connection diagram in Fig. 11.

As the load at times might be short samples of cable or joints, it was necessary to include condensers to smooth out the voltage. These 100,000-volt condensers are of a special " English Electric " design, and are mica-insulated and oil-immersed.

All the busbar and switching arrangements had to be supported from the floor to allow for the overhead crane passing over the testing area. The busbars are $2\frac{1}{2}$ in. diameter brass tube, with 8 in. diameter spheres at all connections. Many of the connections are arranged to swing round for use on either of two busbars as occasion may demand. The supports are of bakelised paper tube with massive corona rings at each end, and the design is such that any flashover takes place quite clear of the paper tube.

All supports, screens, and structural work are solidly earthed and control circuits and metallic structures containing H.V. apparatus are all held at a definite potential. The careful layout of the plant and the consideration given to these apparently minor points has resulted in very quiet operation, free from brush discharges.

A number of red warning lamps are mounted on the screens and control panels, and interlocks are provided so that it is impossible to close the main oil switch until—

All gates are closed.
The crane is at the safe end of the test room.
The busbars are de-earthed.
The induction regulator is in minimum voltage position.
The alternator busbars are at normal voltage.

A remote-controlled, motor-operated, switch earths all three busbars, and magnetic bolts make it impossible to open the gates until the plant is earthed.

Indicator lamps on the control desk show the position of the main induction regulator, and the heating load regulator. This latter is equipped with alternative automatic control to maintain a constant current on the cable without attention.

It is believed that this is the most complete, most flexible, and most up-to-date H.V. cable testing equipment at present in existence.

Line Surges & their Effect on Transformers.

The most elementary fundamental theory of transformer design shows that the voltage per turn is a function of the output and not of the line voltage. For many years therefore designers calculated the amount of insulation to be used between turns on the basis of the voltage per turn only, and the value of the line voltage was not taken into account. When overhead transmission began to be used and voltages were increased, it was found that breakdowns between turns of transformer windings became comparatively frequent, and that these troubles usually occurred on the turns nearest the line terminals. Without knowing much about the causes of these phenomena designers began to design the insulation between turns from the basis of line voltage almost ignoring the normal voltage per turn ; and they also increased the insulation on the line turns, grading the amount from a maximum on the turns immediately adjacent to the line, through approximately 3 to 5 per cent. of the total number of turns, to the normal insulation in the body of the winding. It was found over several years of experience that this practice very considerably reduced the troubles due to failure of insulation between turns.

In course of time it became known that the above troubles were due to surges generated in the transmission line due to switching, arcing grounds or lightning, but very little was known of the real character or value of such transients. It is only in recent years that much practical investigation of these phenomena has been carried out, and this has only been rendered possible by the development of the klydonograph, and the cathode-ray oscillograph. The latter was primarily a laboratory instrument, but the former, on account of its very simple construction, was suitable for investigating actual conditions on transmission lines, and by its use much valuable data has been secured. More recently, however, the cathode-ray oscillograph has been developed into an instrument that can be used in the field, with the result that very complete information regarding transient phenomena is now available.

In order to investigate the effects of surges on apparatus, particularly transformers, surge generators have been built, and at the present time it is possible to produce artificially a transient wave having the enormous value of five million volts.

Actual tests in the field have shown that switching operations rarely cause transient voltages greater than twice normal, and the maximum voltage ever recorded did not exceed five times normal. Also it was found that a surge due to switching was distributed over the entire transmission line with very little attenuation, indicating that such phenomena are of comparatively low frequency. On the other hand it has been found that surges induced in transmission lines by lightning discharges produce transient voltages having crest values as much as fifteen times normal, and furthermore that the waves are of very steep front, in some cases actually attaining the crest value in two micro-seconds. Information of this nature recently secured under actual service conditions is of enormous value in enabling designers to produce transformers capable of reliable service on the highest voltage systems and under the most severe climatic conditions.

Surges cause flash over of insulators, and on account of the difficulties of repair where long transmission lines pass through wild country, it is the practice to increase the insulation of the line to a point where flashover is extremely unlikely. Surges induced in the line are not a function of line voltage, but they depend to some extent on the height of the line. It has been found that the use of an earth wire above the transmission line materially reduces the surge values. If the high insulation of the line is carried right up to the transformer terminals there is a greatly increased risk of a dangerous surge entering the transformer itself. It is therefore a very desirable and sound practice to insulate the line adjacent to the apparatus to a lesser extent than the remainder of the line, since this provides a means of relieving the apparatus of serious over voltages, and the repair of line

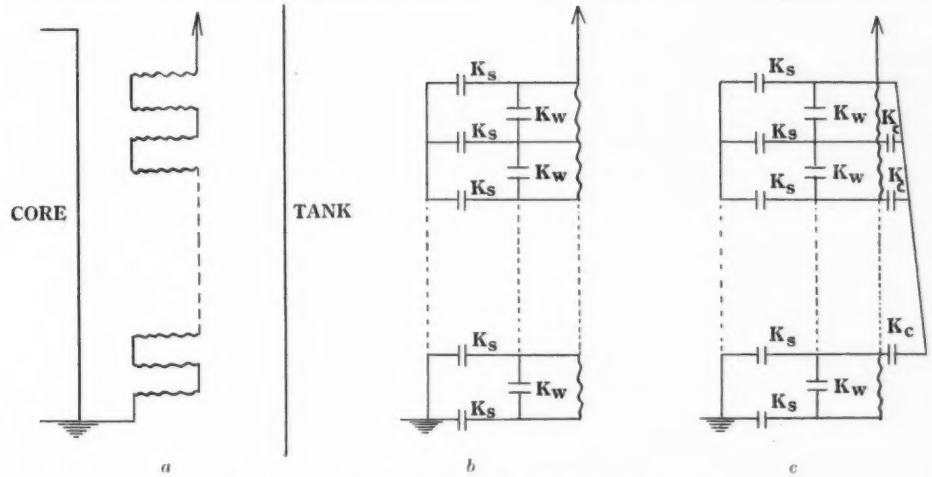


Fig. 1.—Capacitances and Inductances in a Transformer.

insulators at this point can be more readily effected. Surges due to lightning being of very high frequency, or having very steep fronts, cause flashover of weak insulators and consequent relief of the line ; a comparatively short length of line with reduced insulation adjacent to the transformer would give reasonable protection to the latter.

Even this practice, however, does not screen the transformers completely from the effects of transient over-voltages, and they must be designed to withstand the worst possible conditions. The reason why a transformer winding, when subjected to a surge, has induced between its turns voltages much in excess of normal is briefly that the winding is not a pure inductance, but it has distributed capacitance. In addition to the capacitance between turns there is the capacitance between winding and core, and also between winding and tank.

The easiest way to understand the theory of the effect of surges on a transformer is to consider a core type transformer with the neutral solidly earthed. Fig 1*a* shows the arrangement of windings relative to core and tank, and Fig. 1*b* shows the equivalent network consisting of the inductance of the winding, and the capacitance in the winding itself Kw, and also the shunt capacitance between winding and tank and core Ks. The charging currents for all except the first element of shunt capacitance must pass through the winding, and this is the controlling feature in causing uneven distribution of stress when the winding is subjected to a high frequency surge or one having a very steep front, but it has little effect on distribution of voltage at low frequency. Could the shunt capacitances be removed there would be no additional charging currents to flow through the winding, and the stress distribution would be even. Although the shunt capacitances, due to the proximity of core and tank to the winding, cannot be removed, it is possible to neutralise their effect. Fig. 1*c* is developed from Fig. 1*b* by the addition of a further system of capacitances Kc, the charging currents for which are supplied direct from the line. By properly choosing the values of these it is obvious that their charging currents can be made exactly equal to those of the shunt capacitances Ks, with the result that the current in the series capacitances Kw will all be equal with consequent even distribution of voltage.

The above describes an ideal state of affairs, but recently a design of transformer has been produced which goes some way towards this end. On the outside of the H.V. winding is placed a metal shield embracing a certain portion of the winding. It is connected to the line end of the winding, and is properly insulated from the remainder of the winding and ground. This is obviously not an ideal arrangement, because it

only attempts to neutralise the capacitance between winding and tank and has no effect on the capacitance between winding and core. Moreover, it is an added complication involving the insulation of a further member. Although it is an ideal scheme in theory it is probable that the present common practice of reinforcing the insulation between turns is the better scheme for all practical purposes.

As explained in the earlier part of this article, for many years transformers have been built with the insulation between turns determined on the basis of the line voltage, and with considerable reinforcement on the end turns. This has been done with only meagre knowledge of the actual transient conditions that might arise, but the result has been a big improvement in the reliability of transformers in service. Before transmission voltages increased to the present high values, an arbitrary rule grew up and was specified by many engineers that one per cent. of the turns adjacent to the line should be insulated to withstand a test of full line voltage for three seconds, and that the insulation should be graded down through a further four per cent. of the turns to that used in the body of the winding. Recent investigations have shown that this rule lacks practical justification, and on the other hand careful research has provided a very sound basis for the determination of the best proportioning of insulation between turns to withstand transient conditions on modern transmission systems.

Further, research has given ample data regarding the characteristics of insulating materials. The relation between the ability to withstand repeated high frequency voltages, and the strength under steady fifty-cycle stress, referred to as impulse-ratio, is well known; and the variation of dielectric strength with temperature and also with time is established. With all this knowledge of transient conditions, and of behaviour of insulating materials under test it is possible to derive a sound specification for the insulation between turns, and tests that are fully suited to factory conditions. The following table gives a suggested standard, 90° C. being chosen as the best temperature because it is about the maximum operating temperature of oil in transformers, and ten seconds as a reasonable time for a satisfactory test. It is understood, of course, that the tests are carried out on sample coils.

Service Voltage kV. (R.M.S.)	Turns next to Line having Maximum Insulation. Number %	10 Sec. Test kV.	Total Turns to be Reinforced per cent.	Turns in Body 10 Sec. Test kV.
11	1·0	7	4·0	5
33	1·0	25	3·0	15
66	·9	40	2·8	25
132	·65	66	2.0	33
220	·3	110	1·0	55

The above table is intended to apply to reasonably large transformers. If the figures for say 66 kV. are applied to a very small transformer in which there must be a comparatively large number of turns, the result is a winding that lacks mechanical strength, particularly on the end turns which are most likely to suffer under mechanical stresses produced by short circuit. It is recommended, therefore, that for the smaller sizes the insulation between turns should be reduced in order to secure the best compromise between strength of turns, insulation and mechanical strength of the winding.

It has been suggested that all transformers should undergo in the manufacturer's works an impulse test secured by discharging a condenser into the winding, the equipment being designed to reproduce a transient condition. In commercial testing it is almost impossible to produce correctly and safely conditions that correspond to actual service, or to measure the voltage stresses applied; moreover, there is the grave risk that some permanent damage may be sustained, which may cause a breakdown after some period of service.

From the above it is seen that transformer designers now have at their disposal reliable data regarding transient conditions that are liable to damage transformers, and it has been shown that present practice of reinforcing the insulation between turns is a satisfactory means of enabling transformers to withstand the effects of all normal surges. It is suggested that the specification given above provides a means of ensuring that transformers are suitably designed from this point of view.

Transformers for the Grid.

After a very extensive investigation of the operating conditions of a number of high-voltage transmission systems in Europe and America, the Electricity Board decided that for the conditions in England the most suitable pressure for the National Electricity Scheme was 132 kV. The investigation also included the desirability or otherwise of using the solidly grounded neutral system, and it was eventually decided to adopt this system for the whole of the 132 kV. Grid, and to arrange the transformers with graded insulation. The illustrations on pages 16 and 17 show transformers built in the Stafford Works of The English Electric Company, and now operating at Yoker, on the Central Scotland Scheme.

These are three-phase units, and the five-limb type of core is employed, as shown in the upper view of the frontispiece. One advantage of this design is that the cross-section of the yokes is approximately one-half of what it would be with the usual three-phase core; consequently, the depth of both yokes is also reduced by about one-half, and there is a very considerable saving in the overall height of the transformer. The main limbs are of a multi-cruciform section, and are clamped with a single row of bolts through substantial castings, there being a pair of castings for each bolt. The frames are built up of welded structural steel with a view to obtaining maximum strength with minimum weight, and to providing the greatest freedom for the circulation of oil, and for the bringing out of leads. They are clamped to the yokes by five heavy bolts at the top and bottom of the cores.

The windings are arranged in the double concentric manner, the neutral end of the H.V. winding, including the regulating winding, being on the inside next to the core. Outside this comes the L.V. winding, and on the extreme outside the main line end of the H.V. winding. This double concentric arrangement has the advantage that the leakage space between H.V. and L.V. windings is divided into two parts, and the ampere-turns effective in producing mechanical stress is approximately halved with the result that the maximum stress produced under short-circuit conditions is reduced to a quarter. Also it is an economical means of obtaining the desired impedance and ratio of losses with reasonable proportions from the point of view of transport.

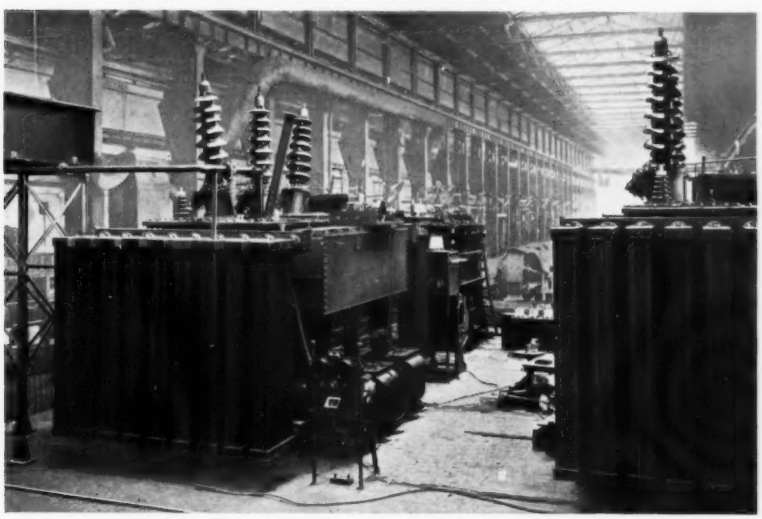


Fig. 1.—Two 10,000 kVA, 132 kV, Three-phase Units for the Grid under test at Stafford Works. In the foreground is the control panel for the On-load Tap-changing Gear with Tap Indicator and Out-of-Step Alarm.

Fullerboard is used for the main insulation, which is split up into a number of layers between which are oil ducts, and between the H.V. winding and yokes the insulation consists of washers and angle rings. The insulation between turns is designed so that on the line turns it will withstand considerably more than line voltage for three seconds, and from this point the amount

of insulation is graded until after 5 per cent. of the turns it will withstand 30 kV. between turns. This reinforcement applies not only to the line end but to the neutral end also, since it is found that although the neutral may be solidly grounded there is the possibility of very severe surges occurring at the neutral end.

An important point in the arrangement of the windings and insulation is the careful provision that has been made for reducing the temperature difference between the copper and the oil by thorough distribution and adequate circulation of the latter.

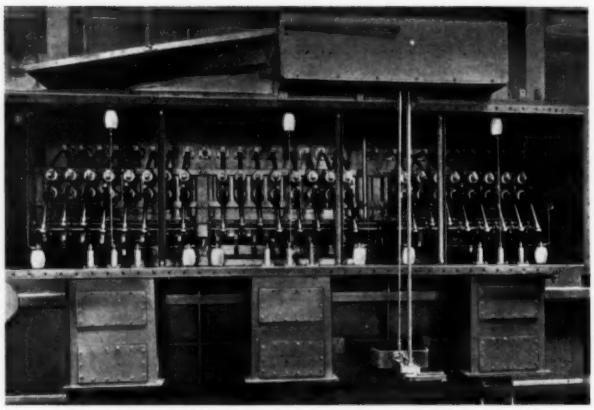


Fig. 2.—Camshaft Type of On-load Tap-changing Gear as used on the Transformers shown on pages 13, 15, 16 and 17.

Since the neutral is solidly grounded, and the insulation is graded, the test applied is an induced voltage of 2·73 times the voltage to ground, which means that under test conditions the line ends of the three phases are raised to a pressure of 208 kV. above ground, and the voltage between the ends of the phases is 360 kV. In order that the effect of this pressure may be reduced as much as possible the winding of one phase is inverted so that the line end is at the top in the centre phase and at the bottom for the other two phases. The line ends of the H.V. winding are brought out by means of flexible stranded cable which is passed up through the centre tube of the bushing to the cap at the top. The bushings are of the condenser type, built up with alternate layers of bakelised paper and tin foil in the usual manner. The outer ends of the bushings are protected from the weather by means of porcelain rain shields, and arcing horns are provided at the flange to prevent cascading under flashover. The dry flashover voltage of these bushings is 400 kV., and under wet conditions the flashover pressure is 320 kV.

The regulating winding on the H.V. side is arranged to give plus and minus 10 per cent. variation in steps of 1·43 per cent. This involves fifteen voltages, and with the " English Electric " scheme there are seven sections of regulating winding in the main transformer and nine leads have to be brought out. These leads are brought through condenser bushings mounted in a pocket at the top of the side of the main tank, and by means of contactors are connected to an auto-transformer which has a mid-point connected back to the main transformer winding. When the auto-transformer is connected across any pair of consecutive tappings a voltage corresponding to half-way between these tappings is obtained. On alternate steps the auto-transformer is connected to one tapping only, in which case the voltage of this tapping is obtained. The contactor gear shown in Fig. 2 is operated on the well-known " English Electric " camshaft controller principle, by a series of double-acting cams and toggle mechanism which ensure correct sequence and positive operation with a quick-break action. The motor-operating gear is mounted in a separate chamber above the contactor chamber, and is remote-controlled from the main switchboard. Control circuits are arranged so that the tap-changer on any transformer can be operated individually or the tap-changers of all the units in a substation can be controlled simultaneously. Under the latter condition a " Klaxon " gives warning if one tap-changer gets out of step with the others. A dial lamp indicator shows which tapping is in use. The operating gear consists of a motor geared to a striker shaft which makes one revolution for each tap position ; for 70° of its revolution the striker engages with a large toothed wheel and moves

the latter through one tooth pitch, corresponding to the camshaft effecting one tap change. Coupled to the striker shaft is a drum controller which is connected to the motor control circuits, and serves to limit the travel of the mechanism after each tap change. The mechanism is locked by means of a follower cam on the striker shaft which engages with a locking plate attached to the toothed wheel. Hand operation is provided, and the design is such that a single turn of the hand-wheel performs one complete tap change.

On page 17 is seen the general arrangement of the contactor chamber and the auto-transformers mounted below. The connections between the two are made through trunks, and the whole of the apparatus is oil-immersed.

The advantages of the " English Electric " arrangement for On-load Tap-changing may be summarised as follows :—

a. The main transformer winding is as simple and reliable as it is possible to make it.

b. There are no parallel circuits in the main winding.

c. No part of the winding is overloaded during the tap-changing process.

d. The whole of the tap-changing gear and operating mechanism is external to the main transformer tank.

The main tank consists of an exceedingly strong welded structure so designed that the complete unit with oil can either be lifted by a crane or jacked up from the bottom. It is supported on a massive welded steel base fitted with swivel ball-bearing wheels.

The cooling system consists of a number of detachable radiators fixed on three sides of the transformer tank. Each radiator consists of a rectangular header at top and bottom with a nest of elliptical tubes connecting them ; they are connected directly to the tank or to main transverse headers that communicate with the tank through two large openings. Simple shut-off valves are interposed at top and bottom between the individual radiators and the tank or main headers, and between the latter and the tank, in order that the tank itself can be completely isolated, and any radiator emptied and removed independently for examination or replacement.

The provision for increasing the radiation of the nests of tubes consists of two centrifugal fans mounted one at each of two corners of the transformer, as shown in Fig. 4. These fans are driven by totally-enclosed motors, and deliver air into a horizontal main duct which passes round the tank underneath the radiators. From this horizontal duct narrow vertical ducts rise between each pair of radiators,

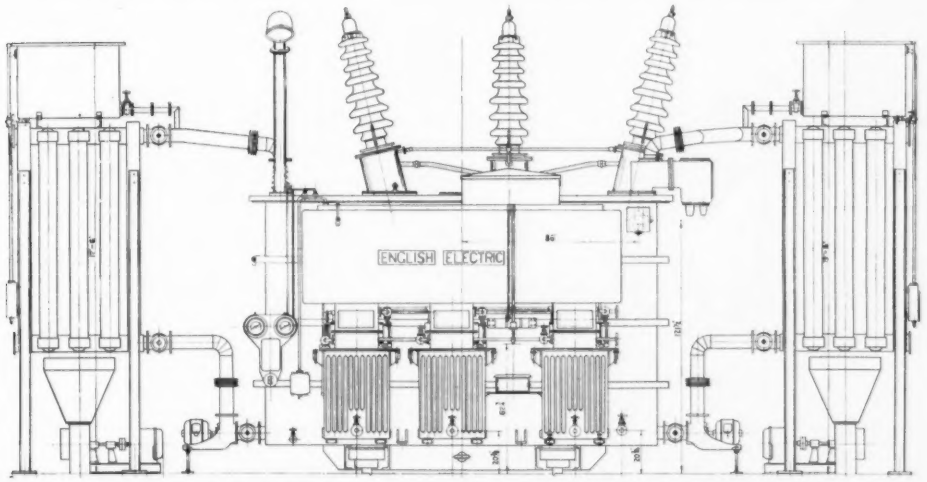


Fig. 3.—Arrangement of Oil Coolers for very large Transformers as described on page 16. The fans for auxiliary air-blast and the circulating pumps are seen at the foot of the coolers.

and each of these risers has a pair of narrow outlets facing the radiator on each side of it at two points in the height. The outlets are provided with flared nozzles in order to disperse the air blast over the whole width of the nests of tubes.

The fan motors are controlled from a cubicle, and are brought into service automatically by the winding temperature indicator equipment when the temperature reaches a predetermined value. The load at which this temperature is attained naturally depends upon the atmospheric temperature and the load condition to which the unit has been subjected; under the extreme condition of an air temperature as high as 40°C., approximately 75 per cent. of the full-load rating can be carried by these units with natural cooling, that is to say, without the fans coming into operation.

For the largest sizes of transformers required for the Grid schemes the above mentioned arrangement of the cooling system is modified (see Fig. 3) by separating the radiators from the transformer tank and mounting them to form a self-contained cooler which is coupled to the tank by large diameter flow and return oil pipes. In the lower pipe through which the cooled oil returns to the transformer a pump is inserted which comes into operation simultaneously with the fan motors and assists the oil circulation. The pump is of such a type that it offers practically no resistance to the flow of oil when it is not running, i.e. under the natural cooling conditions. The forced air cooling of the cooler is produced by a fan mounted immediately underneath it which delivers air on to the radiators in a similar manner to that already described.

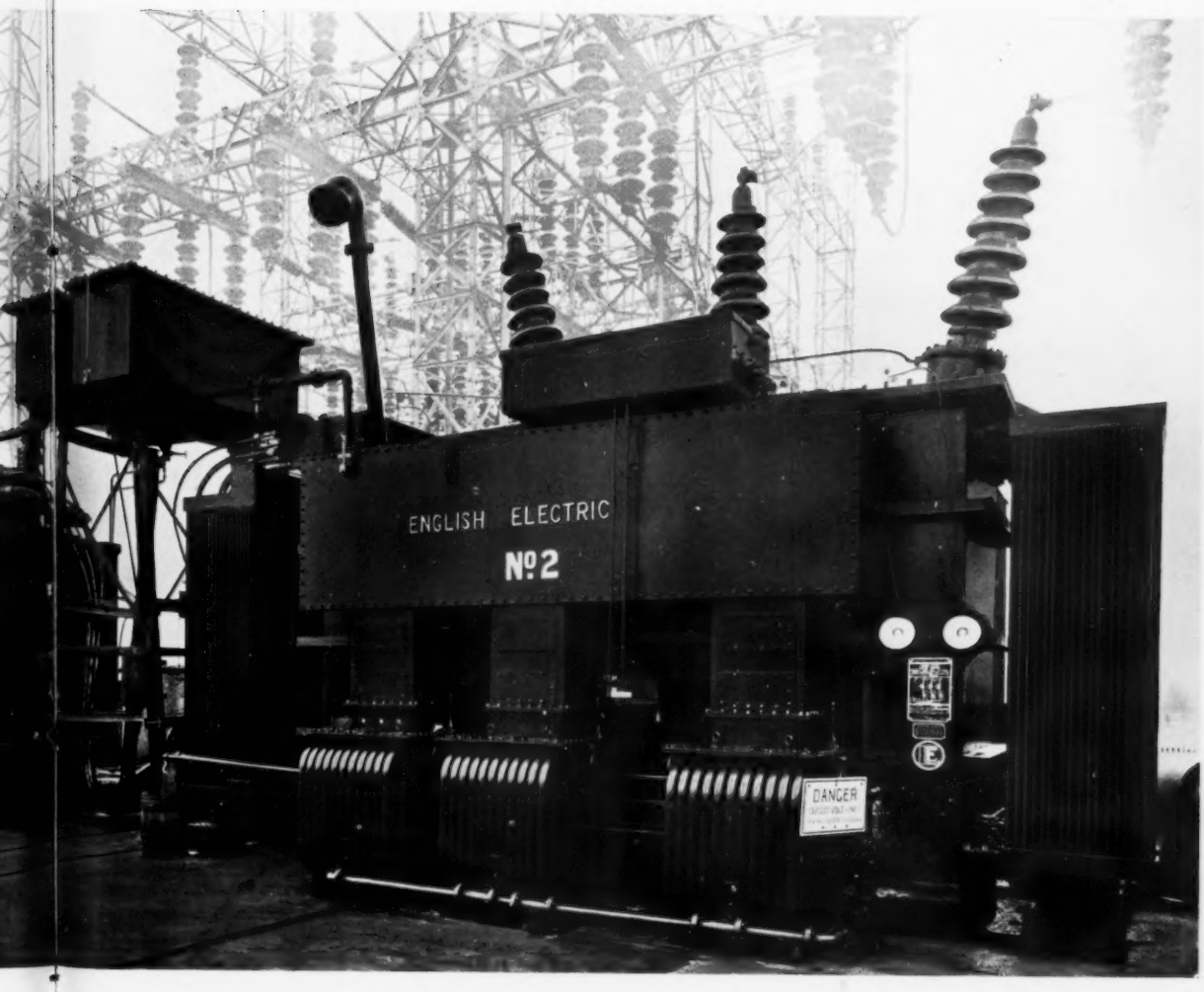
Two of these coolers are used for each transformer, an arrangement which has the incidental advantage that one may be taken out of service temporarily for cleaning, etc., and the unit will still carry a proportion of its load. Another important detail is the careful provision that is made within the transformer tank for guiding the circulation of the oil to the core and windings in the most effective manner. In this design an oil expansion vessel is mounted over each of the coolers.

The units illustrated have two dial type temperature indicators mounted on the side of the tank, one to indicate the oil temperature and the other the winding temperature. The latter is actuated by means of an "English Electric" winding temperature device

Figs. 4 & 5.

The Yoker Substation of the Central Scotland Electricity Scheme. The illustrations show two 132 kV., Three-phase Transformers each of 15,000 kVA. now in operation with On-load Tap-changing Gear. The larger picture shows the Tap-changing equipments consisting of the motor-operating gear at the top, with the switching cabinet connected by trunks to the three auto-transformers. The expansion vessels for the two units are mounted on a separate structure between them.

The upper view, in which the 270-feet tower of the Clyde Crossing can be discerned, shows the two motor-driven fans for the auxiliary air-blast cooling of each transformer at high loads. Some of the narrow air nozzles can be seen between the radiators.



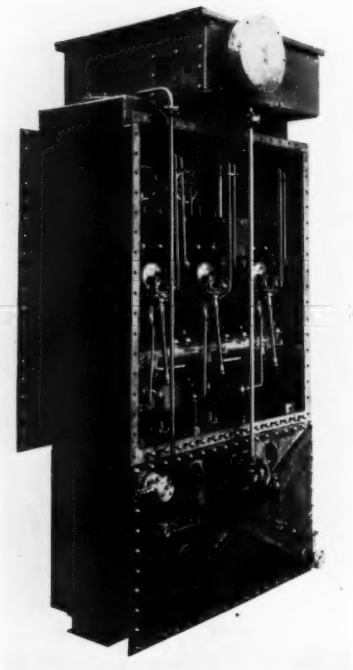
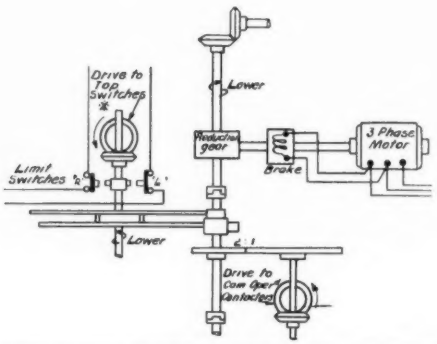
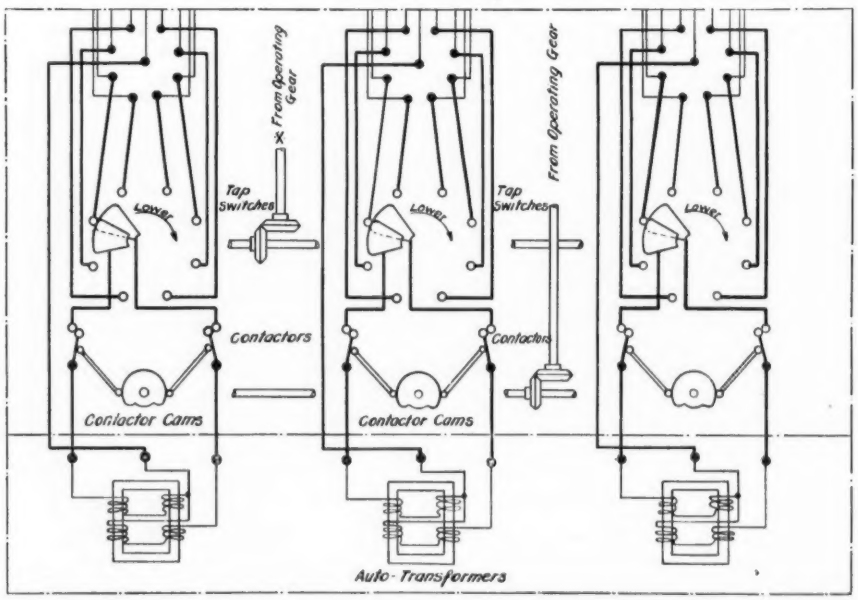
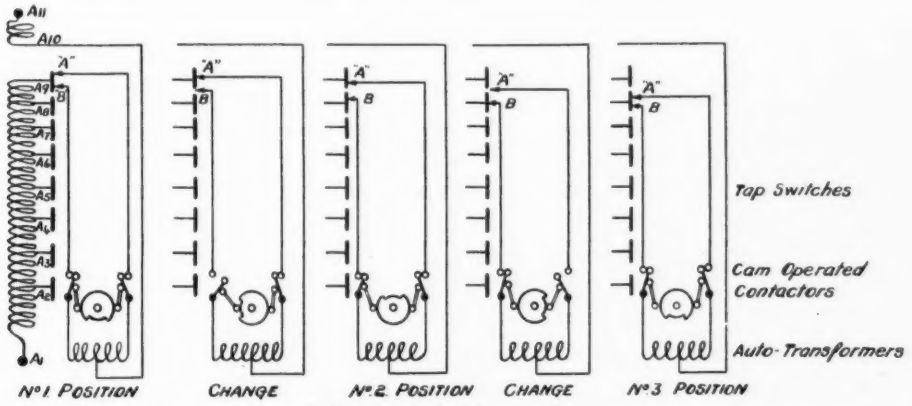


Fig. 6 & 7. On-load Tap-changing Gear of the Company's latest design as used on 33 kV. Transformers for the Central Electricity Board. Complete transformers fitted with this apparatus are shown in the frontispiece, and in Fig. 12, page 26. The diagram shows the arrangement of the parts in the two upper divisions; the bottom tank contains the auto-transformers.







Tapping Position	1	2		3	4		5	6		7	8		9	10		11	12		13	14		15
Transformer Tapping No	A9	A9	A8	A8	A8	A7	A7	A7	A6	A6	A6	A5	A5	A5	A4	A4	A4	A3	A3	A3	A2	A2
Contact "A"	O	O		O	O		O	O		O	O		O	O		O	O		O	O		O
Contact "B"	O		O	O		O	O		O	O		O	O		O	O		O	O		O	O

O Indicates that Contact is made on Transformer Tapping

Fig. 8.—Diagram and Chart showing sequence of the On-load Tap-changing Operations in the Gear illustrated opposite and described on page 20. The general principle for obtaining the various tap voltages is the same as on the 132 kV. units already described.

which is specially constructed to measure the true winding temperature with a negligible amount of time lag.

In addition to the 132 kV. primary transmission lines of the Grid, the Central Electricity Board are erecting also a number of secondary lines most of which will operate at 33 kV. Examples of transformers for use on these lines are illustrated in the lower views of the frontispiece. All of these units are provided with On-load Tap-changing Gear, and are cooled entirely by natural radiation, i.e., there is no auxiliary air-blast equipment as in the case of the 132 kV. transformers.

The cores are constructed in a similar manner to those of the 132 kV. units already described, but for sizes below 10,000 kVA. the usual 3-limb core is used. The windings are arranged in the single concentric manner, the H.V. winding, consisting of a number of disc coils, being outside the L.V. winding, which is of the continuous spiral form.

In this case also the tappings are on the H.V. side; they are situated at the centre of the column of coils and arranged so that whatever combination is in use, the windings are retained as symmetrical as possible. The tappings are brought up by insulated cables enclosed in a

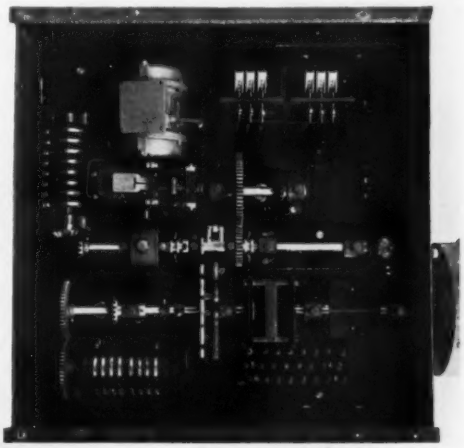


Fig. 9.—Plan View of the operating mechanism of the On-load Tap-changer illustrated on the opposite page.

bakelised paper tube to a point opposite the bushings in the tank side, and are taken through these to the tap-changing apparatus. The various tap voltages are obtained by the use of an auto-transformer in practically the same manner as described in connection with the 132 kV. units, but the switching equipment is of the Company's improved design as shown in Figs, 6, 7, 8 and 9.

The various connections for each phase are made by means of a selector switch mounted between two vertical plates of heavy insulation. This switch works in conjunction with two contactors, the complete group being driven from one motor and mechanically connected so that the timing and sequence of the operations are definitely fixed. Apart from the necessary modifications to the mechanism, the only important point in which the general arrangement of the parts differs from the 132 kV. tap-changing equipment lies in the incorporation of the auto-transformers in the lower part of the tap-changer structure in a separate oil-filled tank. As before the whole of the switching gear is oil-immersed.

The tanks of these units are of heavy boiler plate and have half-round ends. The tap-changer structure is mounted on one side but is detachable for transport. On the remaining sides of the tank are fitted radiators of the same type as those described earlier in this article. Connection to the windings is usually made through porcelain bushings of the outdoor-type, but in some cases cable boxes are provided for coupling up to single-core cables.

Progress of Transformer Design.

Pressures, Outputs and Cooling Methods.

Any attempt to appreciate at their proper value modern developments in the use and manufacture of static transformers necessitates some consideration of the historical side of the subject, since many principles of design now being used were employed in the earliest transformers made.

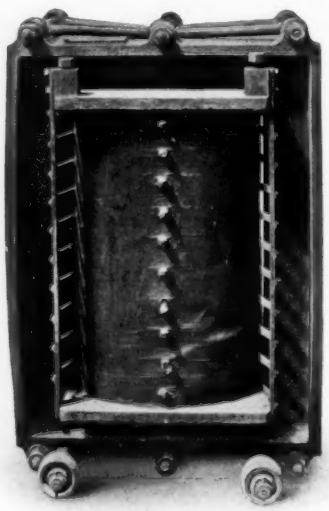


Fig. 1.—A 30 kV A., 2,000-volt, 40-cycle Transformer supplied to the Derby Corporation in 1894.

Fig. 1 illustrates an air-cooled transformer supplied as far back as 1894 by one of the Associates of the English Electric Company. The feature of interest is the use of the Semi-Core construction which has recently become standard for small single-phase transformers built by this Company. But although the principle of design is not new, tremendous advances have been made in the physical properties of the materials, and in details of design, which are reflected in the performance, and of course in the cost. This is illustrated in the following table :—

	Old Transformer	*Modern Transformer*
Iron loss, watts ...	570	200
Copper loss at 75° C., watts	400	700
Total loss at 75° C., watts	970	900
Weight of copper, lbs.	500	190
Weight of iron, lbs. ...	1000	250
Total Weight, lbs. ...	1840	520

A further development of this type of transformer is known as the Distributed-Core type, an example of which is shown in Fig. 2. This design is now used when very high efficiency is desired and considered to be economically justifiable in spite of the increased cost of the unit. Investigation shows that this type was being supplied by an Associated Company as far back as 1893.

Recent developments have included a very rapid increase in the voltage of transformers. Here again, it is of interest to find that in 1890 a 50,000-volt unit was manufactured by the same Company, and that it is still in operation. This transformer, in spite of its 50,000 volts, is actually air-insulated, and in this connection it may be observed that many of the highest voltage laboratories existing to-day are equipped with air-insulated transformers, as for example, the million-volt testing equipment at the National Physical Laboratory. The transformer in question was wound with cotton-covered wire, and the main insulation consisted mostly of rubber applied in layers 2 m.m. thick. Another interesting feature is that although it is a single-phase unit the windings are arranged on three limbs. This style of design is sometimes put forward to-day for very large single-phase transformers, the reason being that the height can thus be reduced sufficiently to permit the transformer to be despatched completely assembled.

The unit was used for demonstrating purposes at the Crystal Palace Exhibition in 1892, and Fig. 3, reproduced from "Engineering" of September 16th of that year, illustrates a flashover obtained at about 45,000 volts; this was described as a very remarkable achievement. It is practically forty years since this 50,000-volt transformer was built, and in that interval the maximum voltage used for testing purposes has been increased forty-fold, since at the present moment a two-million volt laboratory is in existence; also transformers capable of operating on a 380,000-volt transmission system are being built.

Next to the phenomenal increase in working voltage the development in size of transformers is most spectacular. Fifteen years ago a 10,000-

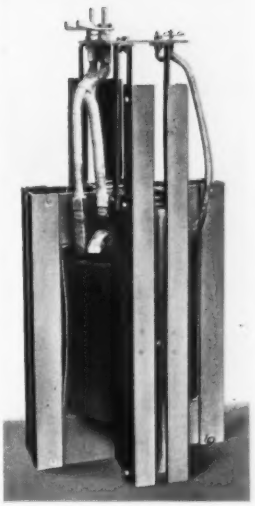


Fig. 2.—Example of Distributed-Core construction for very high efficiency.

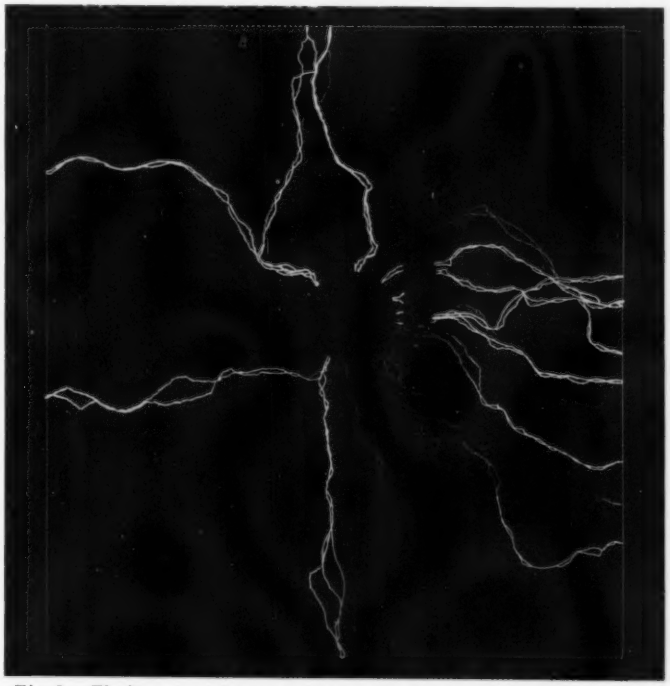


Fig. 3.—Flashover round the edges of a glass plate 2 ft. square at 45 kV., demonstrated in 1892.
[Reproduced by kind permission of "Engineering."]

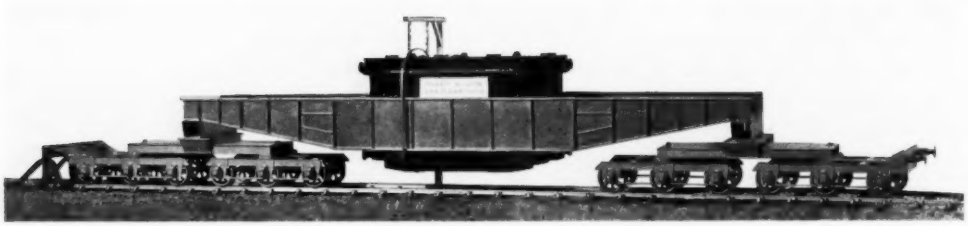


Fig. 4.—Model of Special 120-ton Truck with 60,000 kVA., 132 kV. Transformer.

kVA. transformer was considered a mammoth, but at the present time 100,000-kVA. three-phase transformers are being built, and furthermore, it is possible so to construct such a huge unit that it can be despatched from the works to site by rail in its own tank and covered with oil. Fig. 4 shows a model of a 60,000-kVA. three-phase 132-kV. transformer on the specially-constructed truck that will be used for its transport. The complete transformer will weigh approximately 125 tons. This weight is small, however, compared with some single-phase units forming 100,000-kVA. banks, recently built in America. Each unit is provided with four windings, the bank being used for interconnecting four different systems, one operating at 220 kV., and the test on the windings for this system was 570 kV. Each single-phase unit as arranged for despatch weighed about 120 tons, and when complete and ready for service its weight is approximately 300 tons. Although it has not yet been found necessary in this country to build transformers of this size, it may be remarked that 75,000-kVA., 132-kV., three-phase units are being built at the present time for the National Electricity Schemes.

The reference in the last paragraph to a multi-winding transformer raises an interesting subject. For the vast interlinking schemes now being proposed all over the world, it has been found necessary to use transformers arranged for coupling together more than two systems. This presents some interesting problems of design, but it is quite possible to build such transformers, and also to provide voltage-regulating equipment in the form of On-load Tap-changers on the various windings. An example of a multi-winding transformer is illustrated in Fig. 5. Fig. 6 shows a three-winding transformer of extremely small output considering it is for service on a 66,000-volt system ; all windings have the full capacity of 50-kVA.

One of the most important problems in transformer design is that of adequate provision for dissipating the heat generated in the core and windings. The earliest transformers were air-insulated, and were cooled simply by natural radiation and convection. After a few years transformers were put into tanks filled with oil, which not only gave greater safety from the point of view of voltage stresses, but also provided

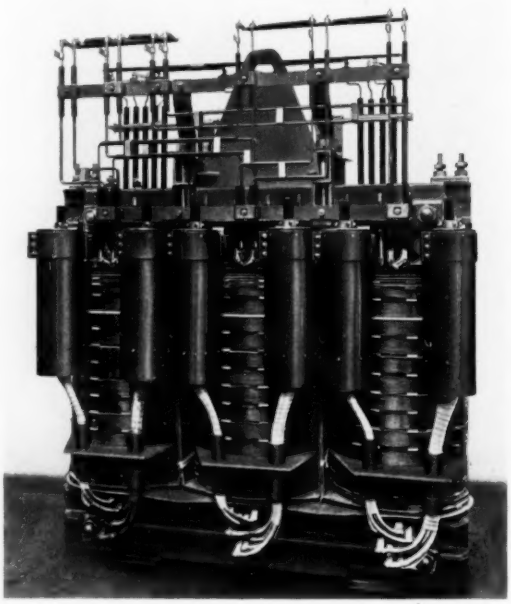


Fig. 5.—1,000 kVA. Three-winding Transformer for Brazil. 40kV./12 kV./2.4 kV., 60 Cycles with Tapping Switches on all Windings.

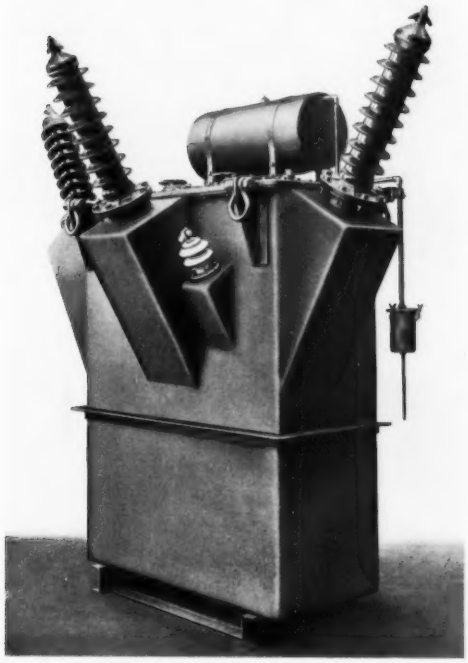


Fig. 6.—50 kVA., Three-winding Unit to be fed at 66 kV. or 33 kV., and to give 7,600 volts and 400 volts on the L.V. Side. Tapping Switches are fitted on the H.V. Side.

a most effective means of transferring the heat generated in the core and windings to the radiating surface. The first tanks were plain, which certainly is the most efficient type for radiation of heat. With the demand for greater and greater outputs, it was found necessary to develop a different type of tank. It was, of course, still possible to use a plain tank of sufficient surface, but the volume of such a tank would have been so great, involving a very large quantity of oil, that the design would have been very expensive. Therefore the first development was to use a fluted tank surface, which, in spite of its lower emissivity coefficient, enabled comparatively large transformers to be built economically. Fig. 7 shows such a tank.

A limit of output was again reached with this type of tank, which is somewhat weak mechanically, and consequently another type was developed. This consisted of a plain boiler plate tank into which round tubes were welded in one or more layers to give the necessary radiating surface; tanks of this type are shown in Fig. 8. This construction is much stronger, and it can be used quite economically for transformers up to say, 4,000 kVA., above which it is not only uneconomical, but it becomes too difficult and unwieldy to handle easily.

A later development of the tubular tank is the employment of elliptical tubes with their major axes normal to the tank surface as illustrated in Fig. 9. This allows a much greater area of cooling surface to be accommodated within a given overall perimeter.

When still larger outputs were called for engineers showed a preference for natural cooling, since in spite of its comparatively high cost, it eliminates auxiliary apparatus and reduces supervision to a minimum. Hence a new departure was made in that the radiating surface was provided in nests of elliptical tubes welded into headers to form detachable units; an example of this design will be found in the frontispiece. By providing on the tank simple valves to which the headers are connected, the radiators can be isolated, drained of oil, and removed without dis-

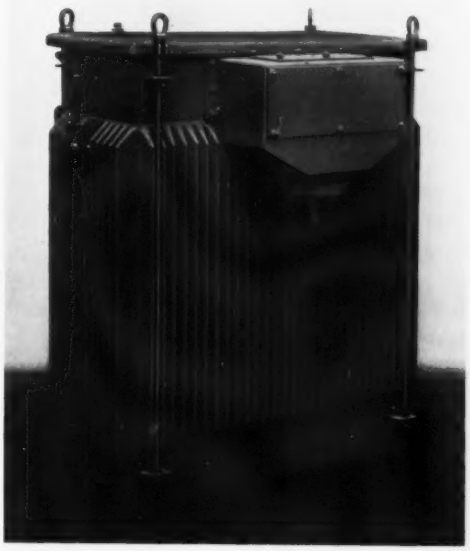


Fig. 7.—Example of a Transformer with Fluted Tank.

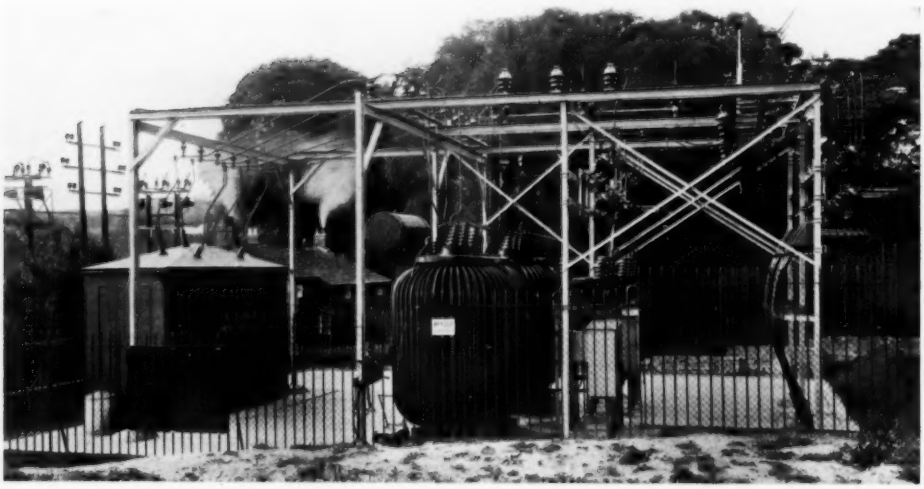


Fig. 8.—An "English Electric" Outdoor Sub-station near Chesterfield. The transformers, which have tubular tanks, are three-phase, 3,000 kVA., 33 kV. units. The equipment includes Oil Breakers, Metering Equipment and Feeder Protection.

turbing the oil in the main tank. The dimensions of such a transformer when prepared for shipment in this way are only those of the main body of the tank. This design enables very big naturally-cooled transformers to be built and transported in their own tanks and covered with oil. This is a very important point since it avoids having to dry out the transformer on site, which, in most cases, is a comparatively difficult and delicate matter. A transformer of this type for 40,000 kVA. has recently been built in America.

In another article in this issue dealing with transformers for the National Electricity Scheme, a description is given of the cooling equipment by which they are enabled to give at least half their normal load with natural cooling, while for higher loads the extra losses are dissipated from the same radiating surface by blowing air on to the radiators. A modification of this type of cooling described in the same article and shown in Fig. 3, page 15, is that in which the radiators form a self-contained cooler mounted apart from the transformer, and a special pump is used to accelerate the oil circulation. An interesting development of the radiator type of tank has been made in U.S.A., whereby each radiator is provided with its own small fan and motor. This has the advantage that the motors may be started up in groups depending on the load on the transformer; moreover, it is not a serious matter if several motors are out of commission, since they can be replaced without shutting down the unit.

Fig. 9.—Tank with Elliptical Tubes. This unit is for a 12,450 kVA., 11 kV., Three-phase Bank, for Federated Malay States.

A bank of these transformers built recently is capable of 100,000 kVA. with natural cooling, and 140,000 kVA. when the auxiliary cooling is brought into operation.

Until recently, in most artificially cooled transformers water was the cooling medium. Many years ago when it was found that naturally cooled transformers of large size were too expensive, the first suggestion was to use water in a cooling coil located in the oil at the top of the tank. By this means there was practically no limit to the amount of heat that could be dissipated, and consequently very economical transformers were possible. Fig. 10 shows units of this design. The cooling coil is usually arranged in several parallel circuits in order to reduce the water pressure required, and it is possible by this construction, coupled with the provision of an expansion vessel for the oil in the main tank, to arrange so that the pressure of oil surrounding the cooling coil is greater than the pressure of water inside it. Thus it is impossible for water to escape into the oil if a leak develops in the pipe. The earlier cooling coils being made of iron, troubles were experienced due to corrosion, and transformer failures resulted. Some designers decided that there was no reason to change the scheme, but that the cooling coil should be made of copper, and this proved so satisfactory that transformers with an internal cooling coil are now almost universal in U.S.A. for large outputs.

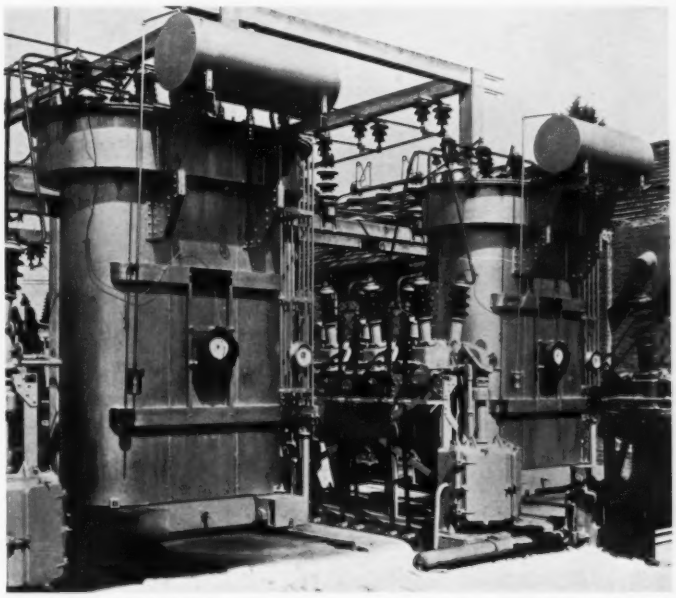


Fig. 10.—5,000 kVA., Three-phase Water-cooled "English Electric" Transformers operating on a 40 kV. System in Brazil. These units have two secondary windings.

When the first difficulties were being experienced, some designers suggested that the water cooling should be done in an entirely separate piece of apparatus, and this resulted in the development of separate coolers with a pump for circulating the oil between the main tank and the cooler, which usually consists of a casing containing a nest of tubes similar to the ordinary surface condenser. Fig. 12 shows a transformer in which this type of cooling is employed.

Referring again to transformers in which provision is made for the dissipation of losses by natural radiation into the surrounding air, a development now being considered is based on the fact that the heat capacity of air is very considerably increased if the air is humidified. The suggestion is that the cooling suface should be lagged with an absorbent material kept moist by means of water, of which only a small quantity would be required. Experiments show that this very greatly increases the cooling efficiency of the radiating surface, and assuming that a water supply is available, it would result in an economical cooling equipment.

Although, as stated above, the first transformers made were air-insulated, and naturally cooled, in later years perhaps 95 per cent. of all transformers have been of the oil-immersed type ; in spite of this, certain users still adhere to the old type, and in some cases, even when the size is too big for natural cooling, air-insulated transformers with air blast cooling are installed. Fig. 11 shows a

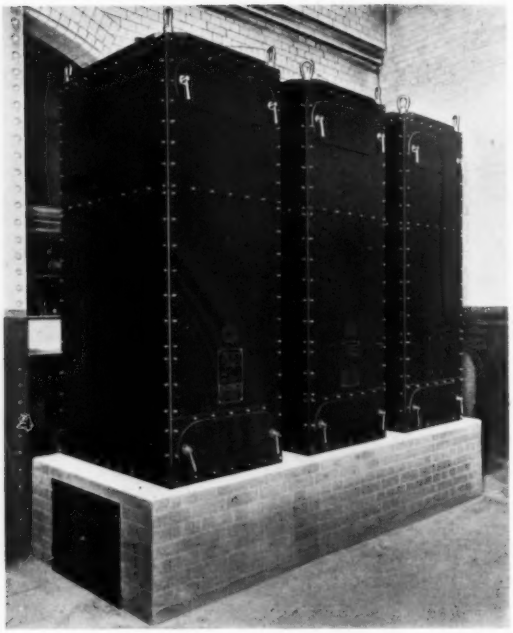


Fig. 11.

A Bank of Air-insulated, Air-blast Transformers operating in London. Part of three "English Electric" 2,000 kW. Traction Rotary Convertor Equipments.

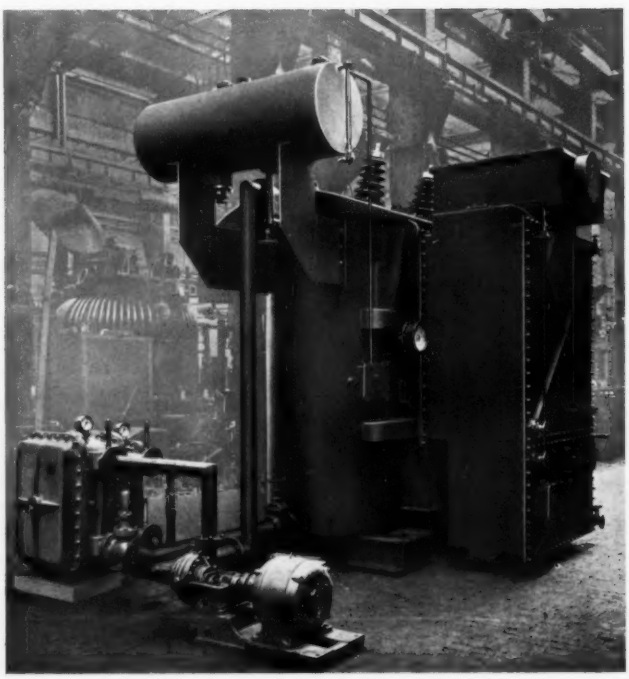


Fig. 12.

A 10,000 kV.A., 3-phase Forced Oil-cooled Transformer with On-load Tap-changing Equipment for use on a 22,000-volt system in Australia.

bank of single-phase transformers of this type. For the larger sizes it is found preferable to use the shell type of construction since this design leads to a better distribution of cooling air through the windings than a core-type transformer; an example of the former is shown in Fig. 13. Nevertheless, the latter type can be used effectively for the smaller outputs.

A fundamental necessity with air-insulated transformers for air-blast cooling is that the treatment applied to the windings shall be such that it results in a very hard and smooth surface to which the dust which may come through with the air will not cling and thereby impede the cooling; also the surface must be such as to radiate heat as efficiently as possible. Fortunately, an extremely good air-drying varnish has been discovered which gives an extraordinarily good finish to the windings, and transformers examined after years of service have shown the windings to be practically as good as new. Transformers of this type can be built only for pressures of certainly not more than 20,000 volts. As an example of the large outputs to which this design has been extended it may be mentioned that some 18,500-kV.A., 3-phase, 25-cycle units are now in operation.

Fig. 14 shows the comparative costs of transformers with various types of cooling for a wide range of outputs, and in so far as capital expenditure alone may influence the type of cooling these curves are of considerable interest.

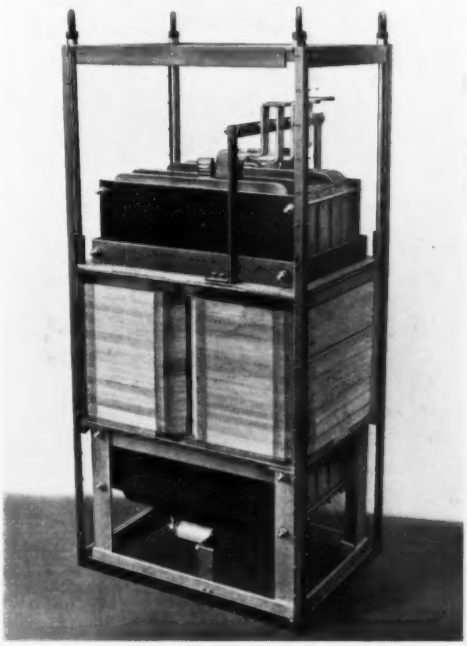
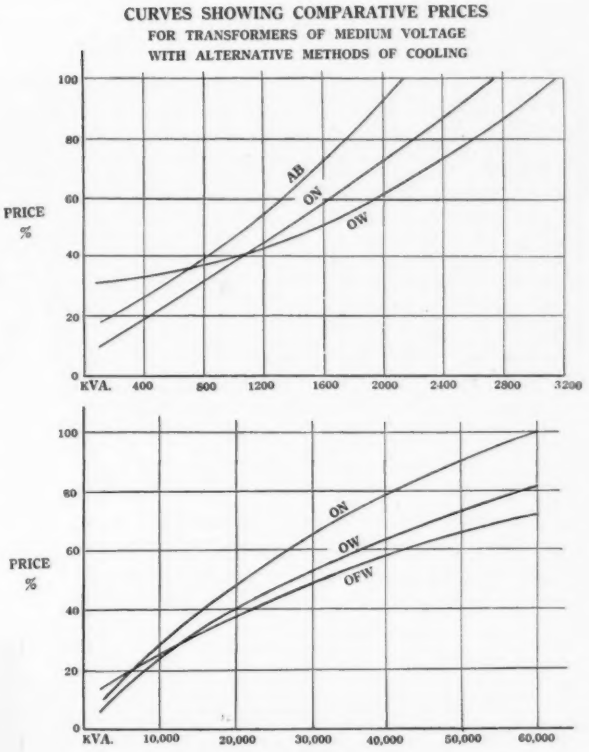


Fig. 13.—Core and Windings of one of the Units shown in Fig. 11.



AB = Air-insulated, Air-blast.
ON = Oil-immersed, Natural-cooled.
OW = Oil-immersed, Water-cooled.
OFW = Oil-immersed, Forced Water-cooled.

Fig. 14.

Transformer and Switchgear Bushings for High Voltages.

The purpose of a bushing is to lead current through the earthed tank or casing of the transformer, switchgear, or other electrical apparatus. It consists of an insulated conductor fixed by means of a flange cemented or shrunk on to the solid insulation. For low and medium voltages, where space is not too restricted, porcelain is generally used. As we know from other insulation problems, increasing voltages demand greater thicknesses of the insulating material or dielectric; as the maximum wall thickness of porcelain that is electrically sound is limited, it is necessary to use combinations of dielectrics in bushing designs. Oils and plastic materials are suitable substances to fill up the space between the conductor and the porcelain, the latter forming the container with a suitable outside diameter to prevent undesirable discharges from the flange to the conductor either radially or along the outer surface. Fig. 1 illustrates these two possibilities of electrical failure of such a bushing.

It is therefore necessary for the designer to know all about the conditions of electric stress along these two main paths. In the radial direction he has to ensure that the potential gradient under service—and test—conditions is below the breakdown gradient of the dielectric at any point.

The field intensity in such a concentric arrangement of two metal electrodes is a maximum at the surface of the inner electrode, and, as the result of experience, critical values have been determined for the dielectric substances the designer has to use.

In the axial direction, i.e. along the surface of the bushing, starting at the flange, no discharge whatsoever should be present at the working voltage, and no excessive discharge should be allowed at the test pressure, as this might lead to the external flashover of the bushing.

It has been found by experiment that the beginning of the first form of discharge coincides with a radial stress of 11 kV./cm. in an imaginary thin film of air between the flange and the dielectric. This discharge, known as "strip discharge," is a linear function of the voltage, increasing in length at the rate of 1 cm. per 5,000 volts (approximately). These values are inversely proportional

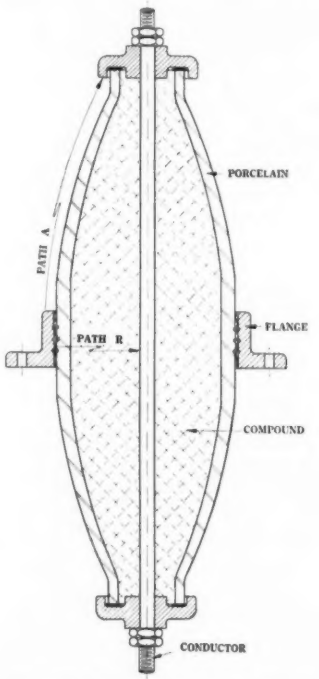


Fig. 1.—Parts of a Bushing showing paths of possible failure.

to the dielectric constant of the insulating material and it is therefore advisable to use insulation of low dielectric constant in order to reduce the dimensions of the bushing. This helps to explain why oil of dielectric constant, 2·3, as against 5 for porcelain, is used for high voltage bushings, the dielectric properties being improved by interposing thin cylindrical barriers to break up the radial leakage path. In addition, the flange electrode is immersed in the oil so that the above mentioned strip discharge cannot take place. Radially the oil is still unevenly stressed, the maximum stress being at the conductor; in-

sulating the latter with a paper tube makes some improvement.

There is one type of bushing where this non-uniformity of stressing is almost eliminated. As early as 1905 R. Nagel patented the principle known as the Condenser Bushing. He showed how it was possible to make better use of the high dielectric qualities of the insulating medium, thus reducing the size of the insulator. If we reconsider Fig. 1 for a moment, we see that this bushing represents a condenser, the conductor being one electrode and the flange the other. If the spacing of these electrodes is very small the difference in the value of the electric stresses at their surfaces is negligible; whereas on a bushing having a conductor of say $\frac{3}{4}$ in. diameter, and a flange diameter of about 4 in., this difference is of the order of 5 to 1. The object of the patent was to sub-divide the one capacity into a series of capacities by interposing a convenient number of very thin metal foils. If the condensers so formed are all of the same capacity then each of them will have to bear the same voltage with a practically even stressing of the dielectric right through the wall thickness. Fig. 2 illustrates a Condenser Bushing.

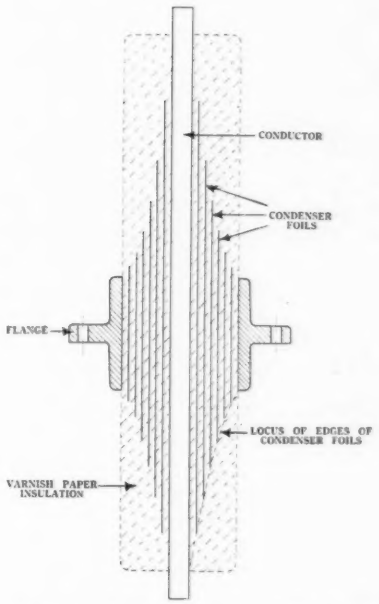


Fig. 2.—Elements of Condenser Bushing.

With equal radial spacing of the foils, their edges lie on a parabolic curve, and have the same potential difference between one another; in other words, the potential drop along the surface of the bushing (path A Fig. 1) is not quite regular, thus slightly reducing the maximum possible flashover voltage obtainable. With equal potential distribution along the surface of the bushing, the radial stressing becomes unequal, owing to the variation in the spacing of the foils. A compromise of the two ideal arrangements will give practical satisfaction. To enable the electrical engineer to use the condenser principle whenever a bushing problem presents itself, he should remember that the surface of the conductor embedded in the insulating material, should be as nearly as possible equal to the surface of the flange or earth electrode, bearing in

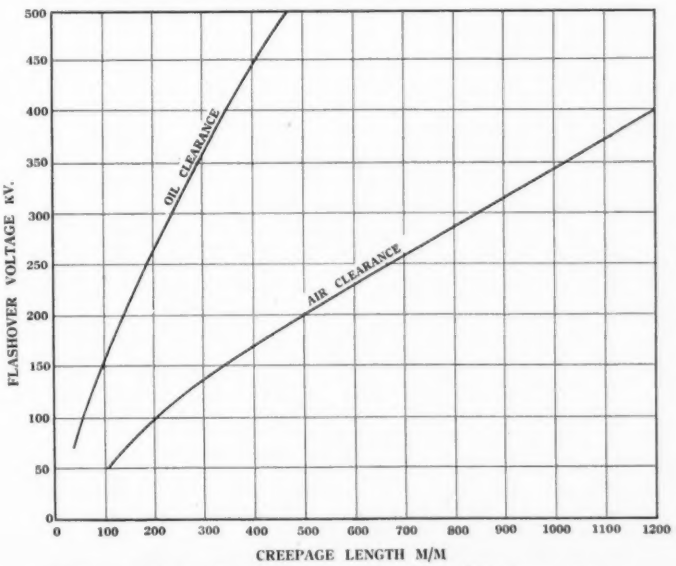


Fig. 3.—Relation between Creepage Length and Flashover Voltage.

mind that the overall length of the bushing is the sum of the two creeping lengths on either side of the flange, and the length of the latter.

The creeping lengths necessary for the different flashover voltages are a matter of experience, and the curves of Fig. 3 give some information on this subject. It is understood that these figures apply particularly to bushings made of synthetic resin treated paper. Special machines are necessary, the paper being wound on to the conductor under the action of heat and pressure to produce a homogeneous material. Metal foils of the right width and length are wound in with the paper at the specified time. If the resin is of the bakelite type a careful baking process has to succeed the winding operation in order to convert the resin into the chemically inert state and produce, in conjunction with the special insulating paper, a product having excellent heat resisting properties.

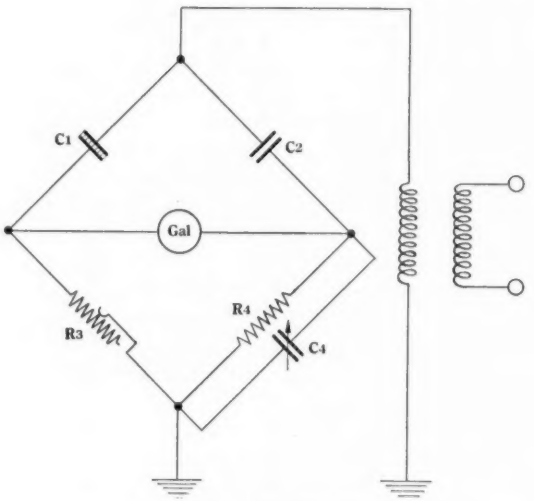


Fig. 4.—Schering Bridge.

At this stage of manufacture the insulator has to undergo most severe tests to prove its electrical soundness. As we know, every condenser, with the exception of an air condenser, when electrically stressed develops losses due to dielectric hysteresis in the insulating material. These losses, or an equivalent factor—the power factor of the bushing—are conveniently measured by means of a Schering Bridge of which a diagrammatic representation is given in Fig. 4. C 1 represents the insulator under test; the galvanometer is of the vibration type.

Measurements are generally made with the oil end of the bushing immersed in transformer oil at 90° C. So far, watt loss measurements have mainly been carried out by the makers of the bushings with the object of safeguarding themselves against the supply of material which might not stand up to service conditions. There can be no doubt that firms not having the necessary testing facilities have sold material which, in some instances, has given trouble in service due to high losses, resulting in heat accumulation inside the dielectric and causing the electrical breakdown of the material. The constant use of the Schering Bridge has enabled manufacturers to improve the quality of their materials, and to establish figures for the power factor or the losses of each type of bushing.

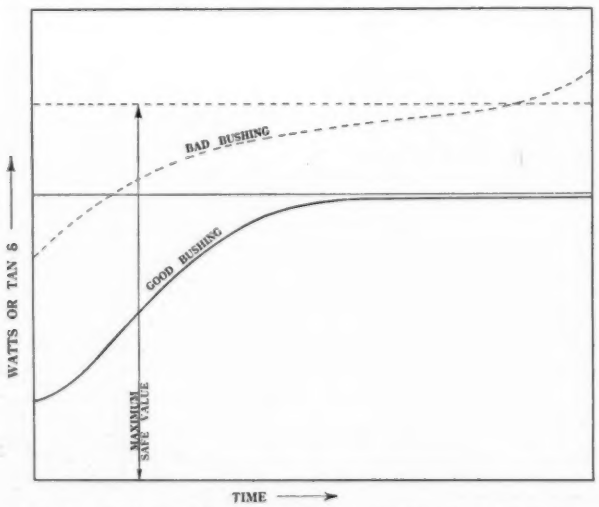


Fig. 5.—Variation of Losses in Bushing with Duration of H.V. Test.

It is one of the main conditions

Fig. 6.—A Group of Condenser Bushings (reproduced by kind permission of Messrs. Micanite & Insulators, Ltd., of London).

that the watt loss be measured at the rated voltage of the bushing or above, the oil end being immersed in transformer oil at 90° C.; the losses reach a final asymptotic value when the bushing is stressed over a period of several hours, see Fig. 5.

A condenser bushing for 132 kV. working pressure as used on the grid schemes will start off at about 15 watts, and reach its maximum value of about 32 watts under continuous stressing of 150 kV. at 90° C. oil temperature. The watt loss at the phase pressure of 76 kV. will be less than $32 \times \frac{76^2}{150^2} = 8$ watts on a transformer at maximum oil temperature, and considerably less on switchgear where the oil does not reach such a high temperature.

It has to be mentioned that bushings for outdoor use are shrouded with porcelain over the air part, the space between the varnish-paper body and the porcelain being filled with special insulating compound. Of the different types of bushing, the condenser type has the smallest dimensions, and is therefore the most suitable type on which to mount current transformers, or to make provision for bringing out tapping leads.

Fig. 6 shows a range of condenser bushings for outdoor use up to 132 kV.

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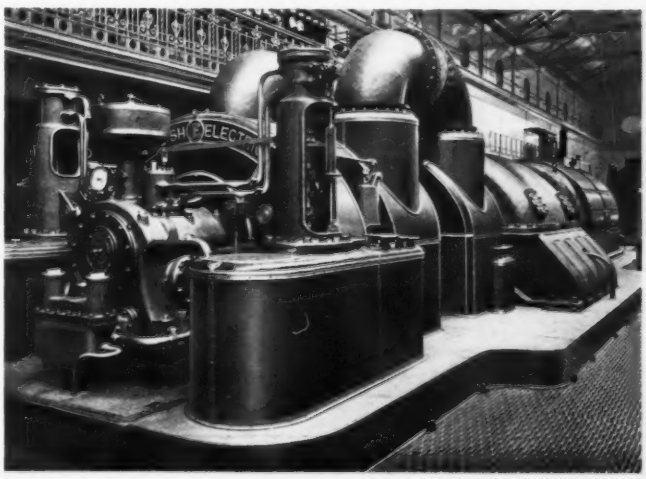

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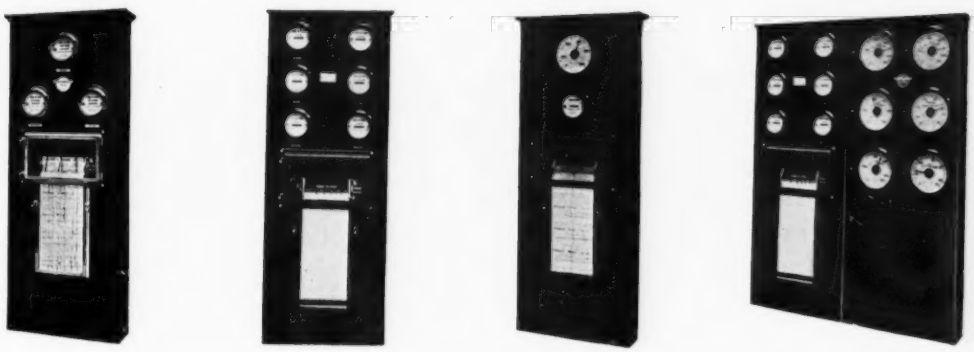

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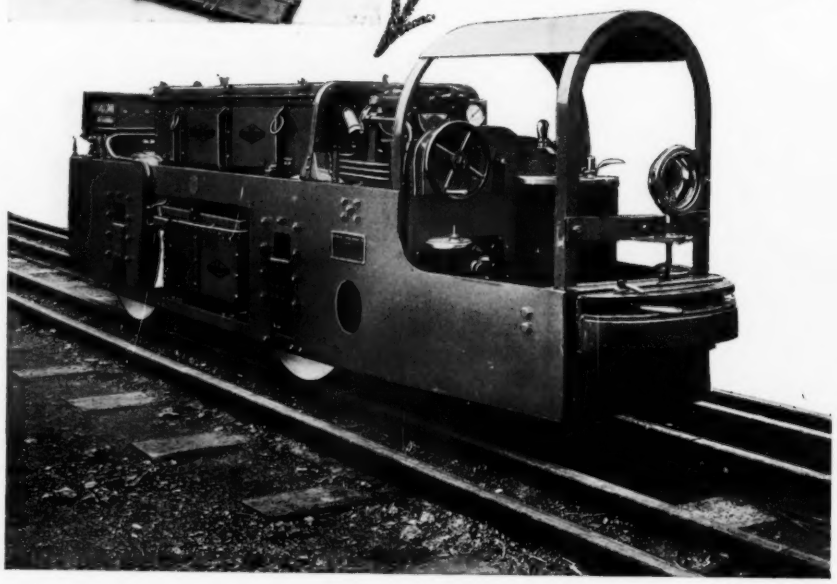

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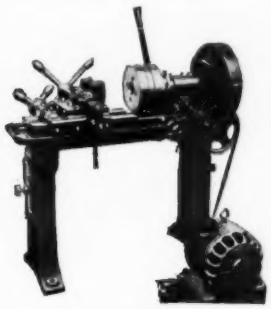

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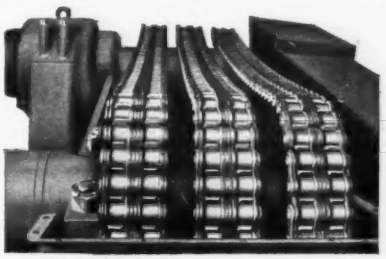

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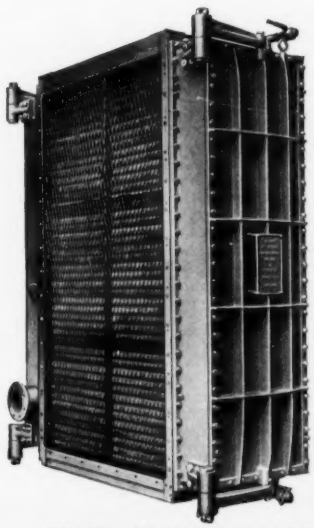

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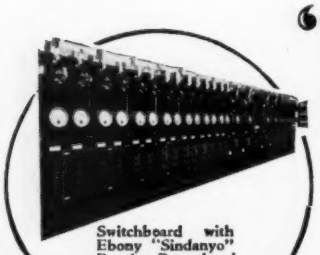

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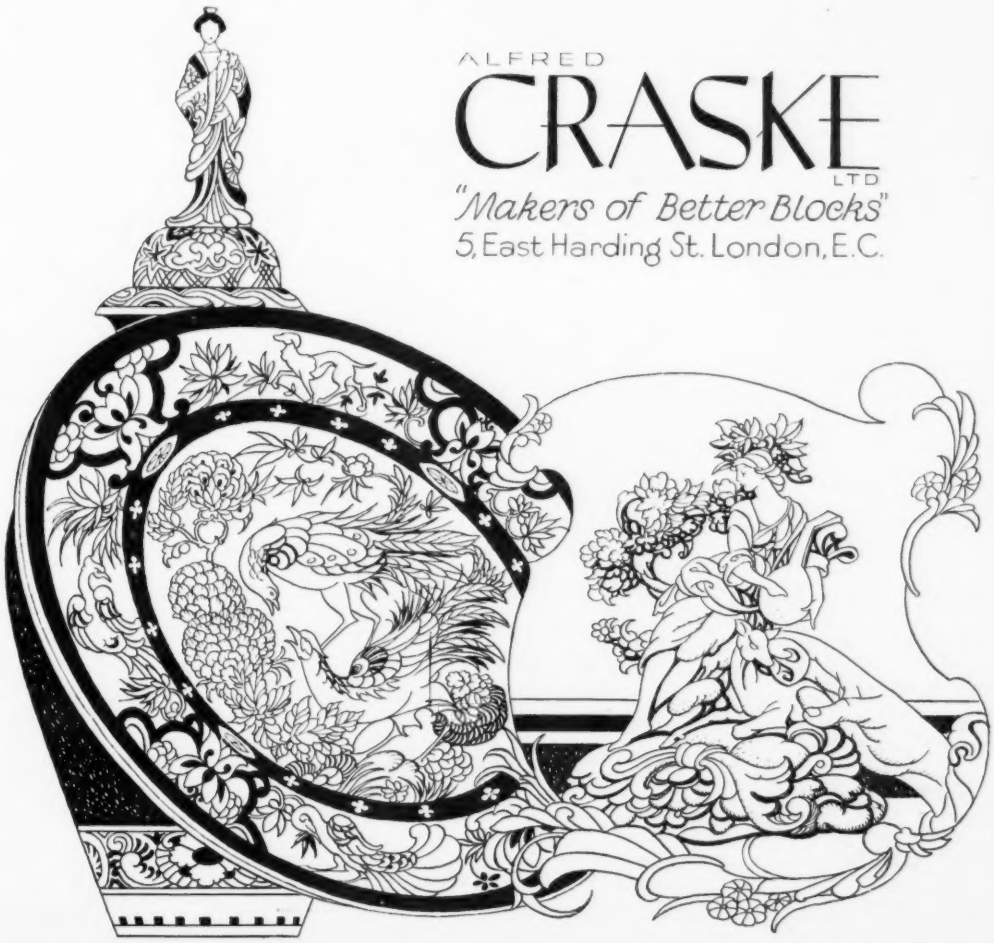

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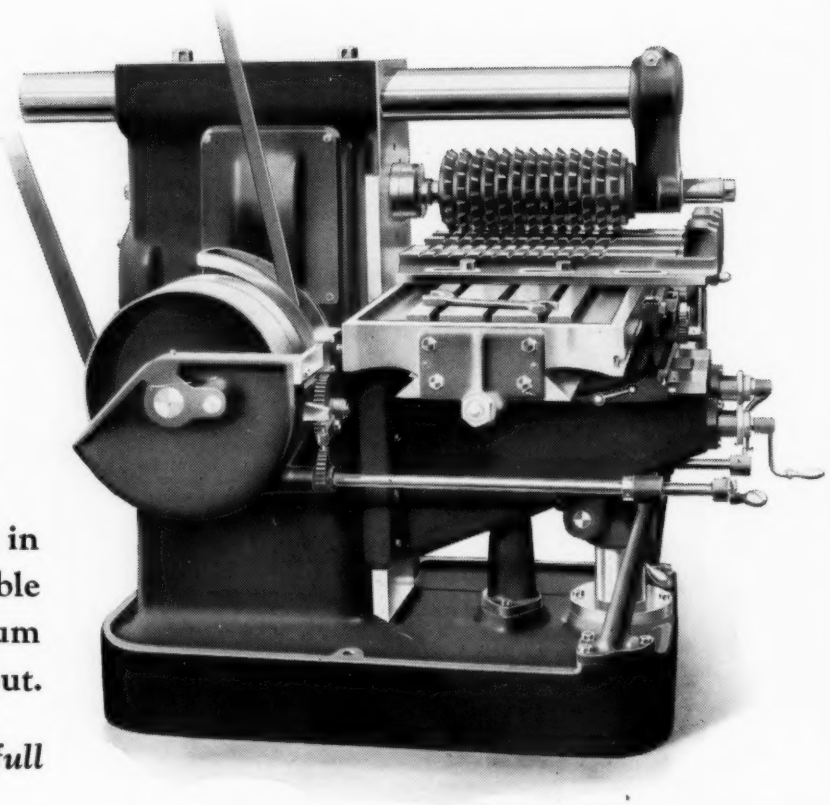

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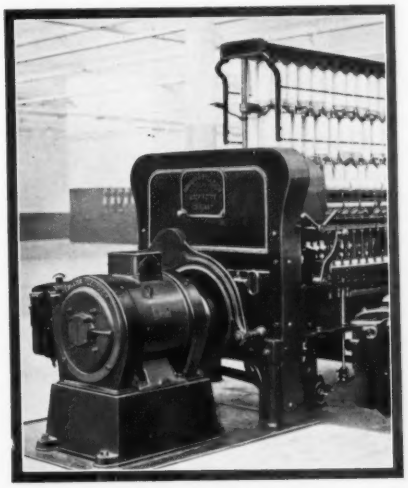

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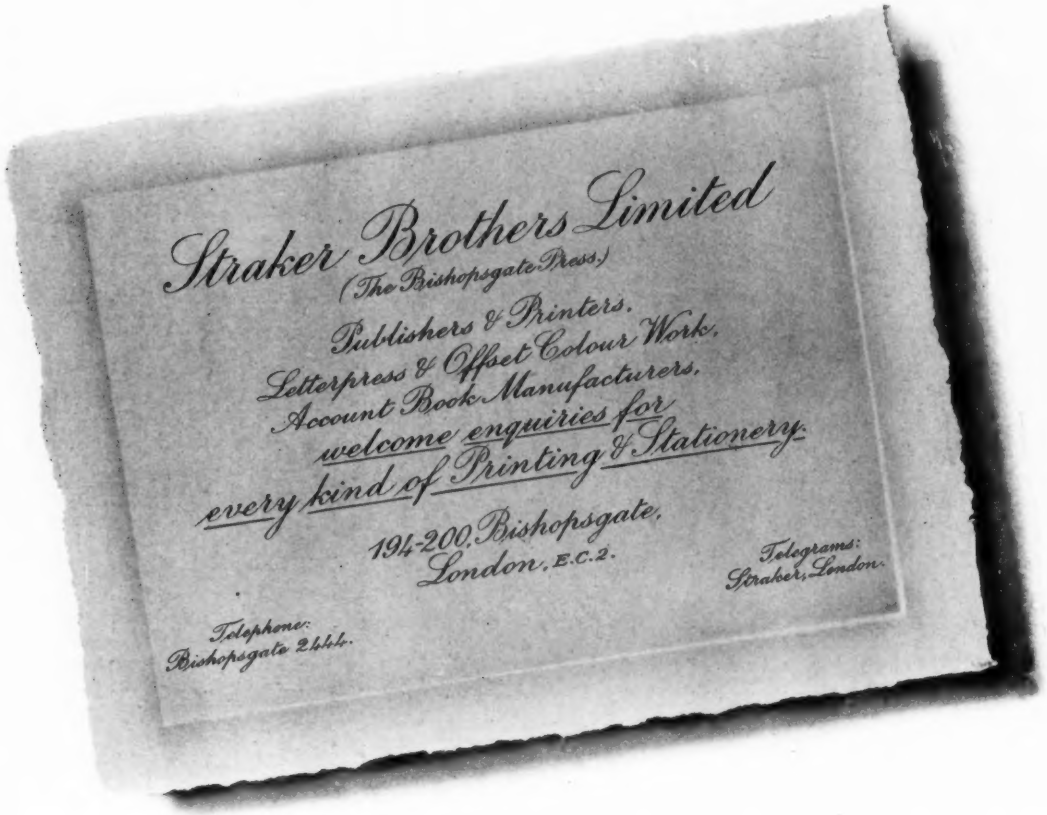

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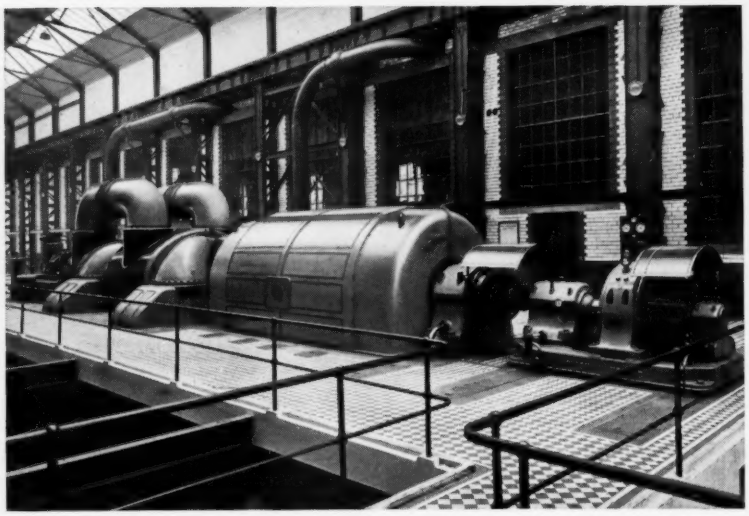

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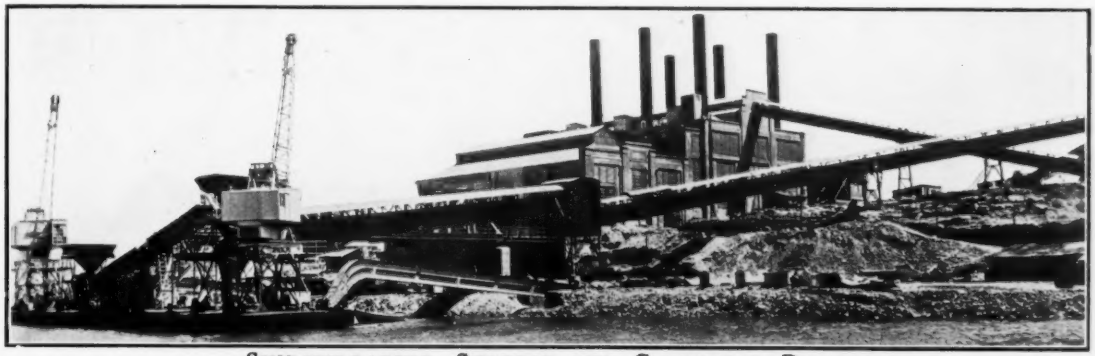

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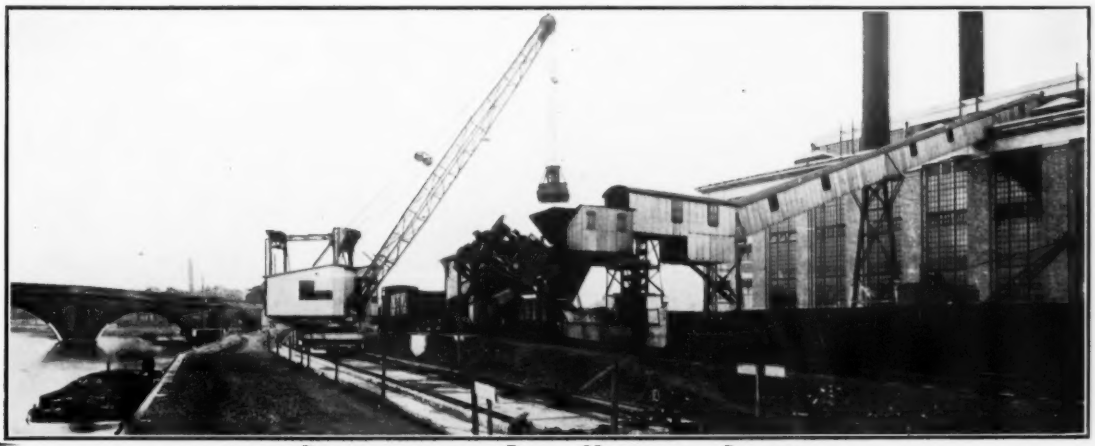

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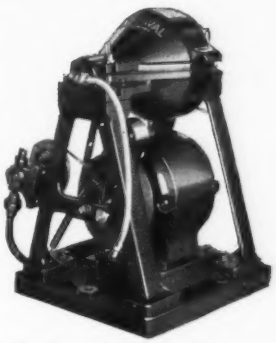

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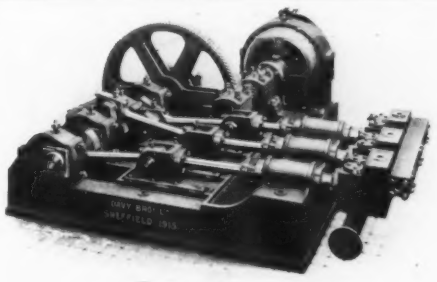

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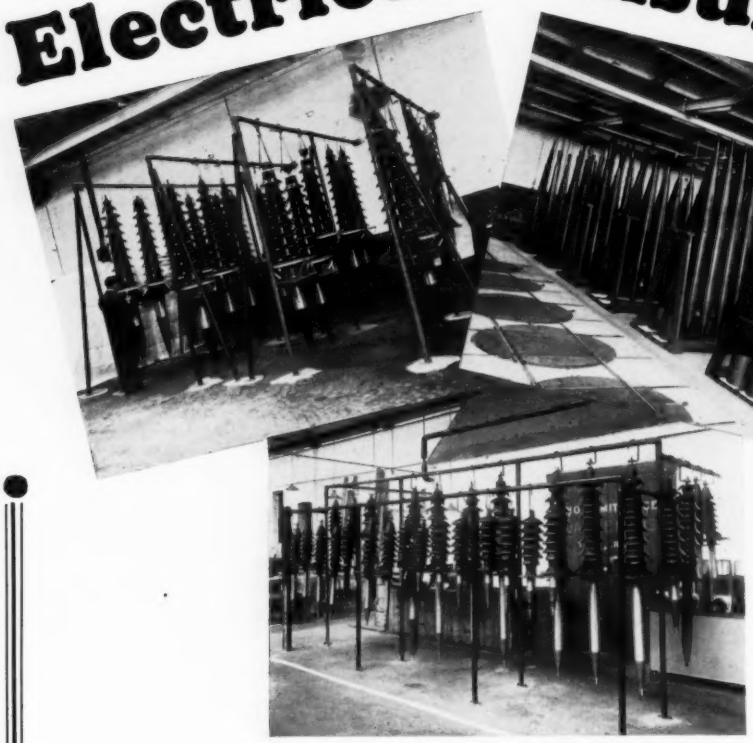

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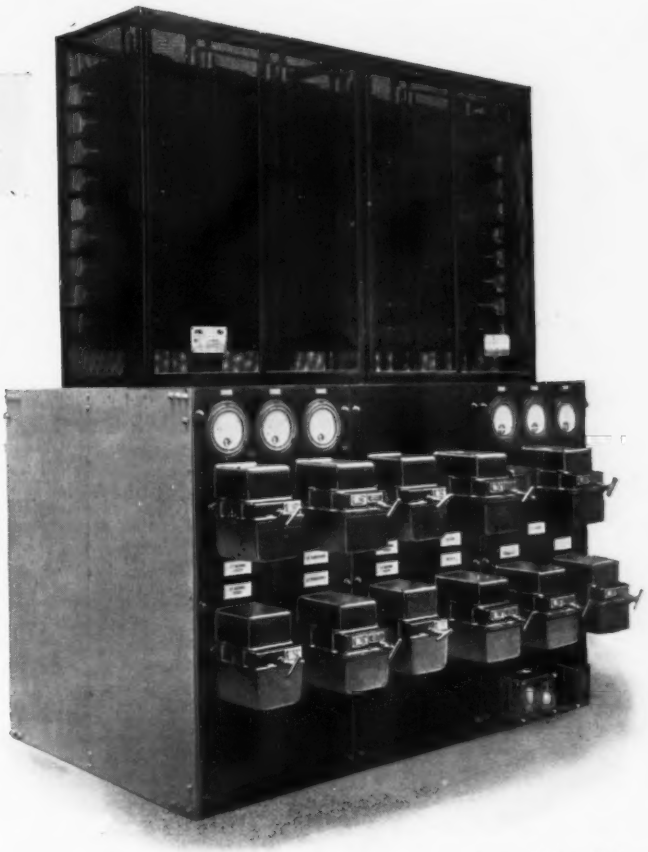

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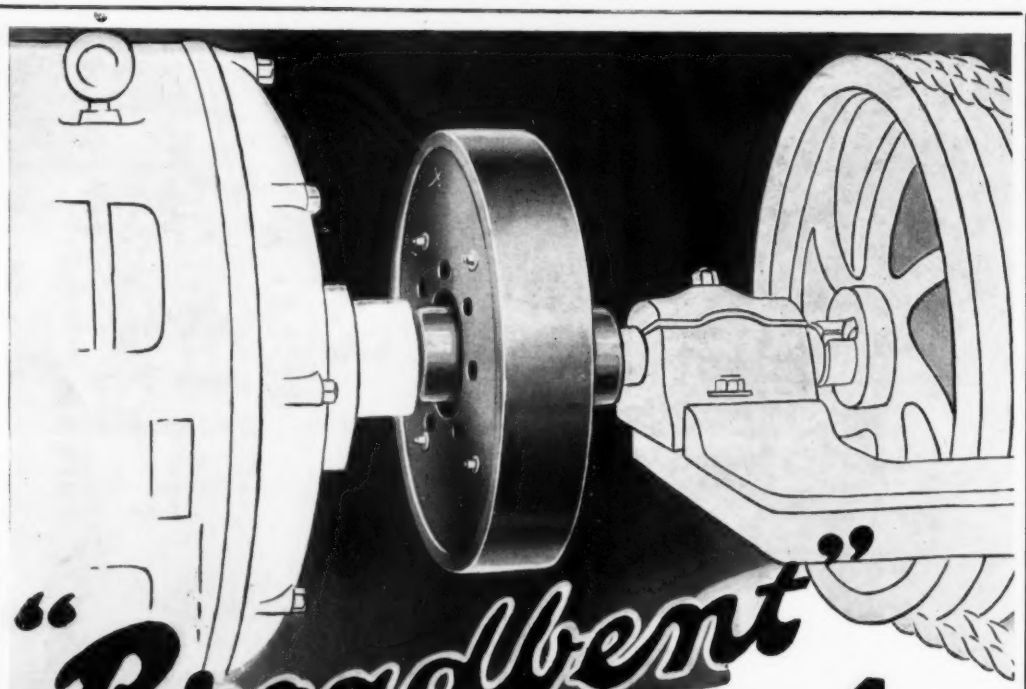

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